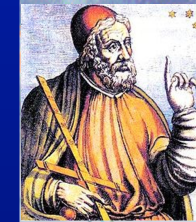


PTOLEMY and Relic Neutrinos

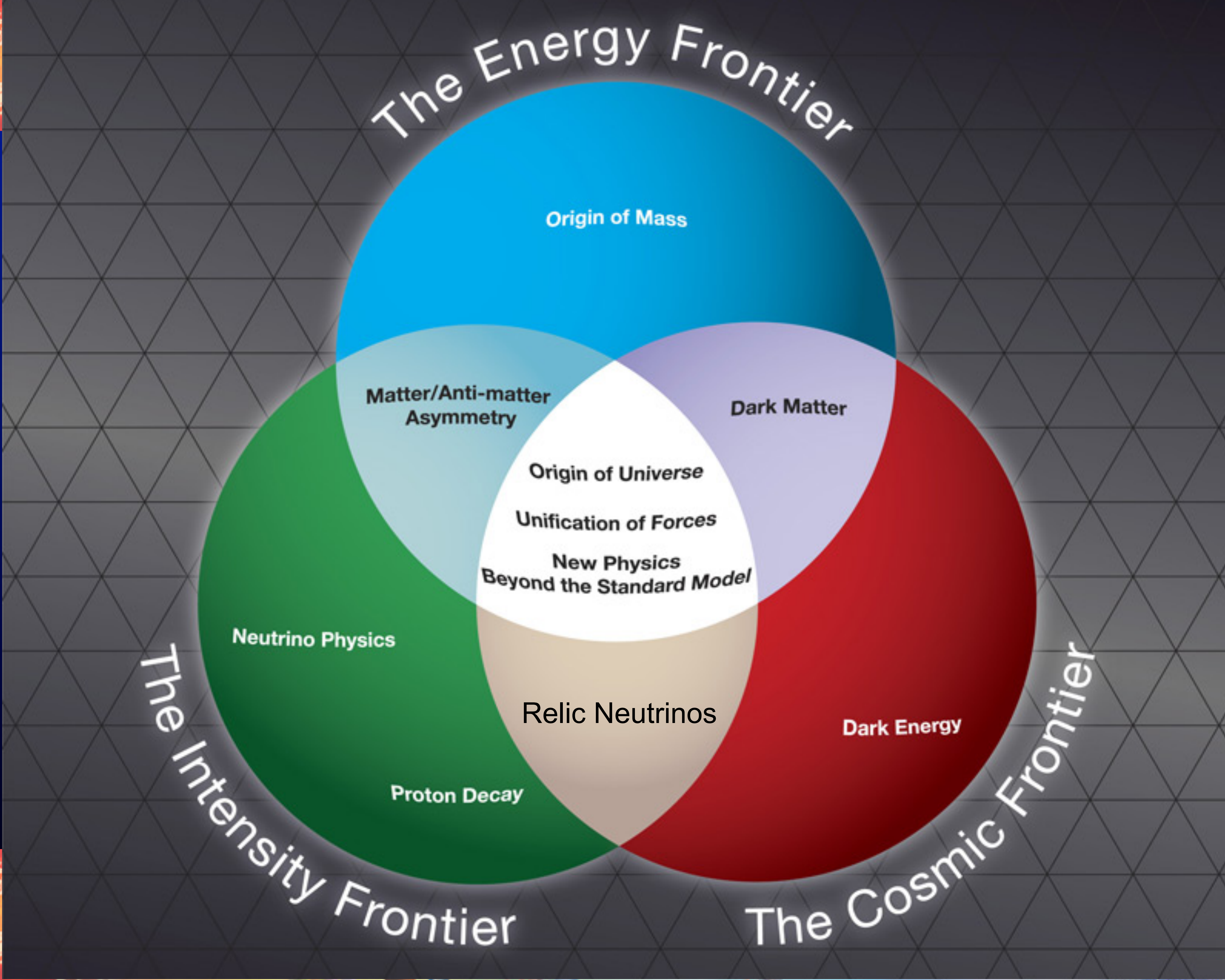
Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

Chris Tully

Princeton University

BNL Cosmic Vision Workshop

October 1, 2015


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Relic Neutrinos
Dark Energy
Proton Decay
The Intensity Frontier
The Cosmic Frontier

Why talk about relic neutrinos?

- Micro-fabrication has changed the landscape of technological possibly in a number of important ways

“Computers in the future may… perhaps only weigh 1.5 tons.”
-- Popular Mechanics magazine, 1949

- The barriers to relic neutrino detection come down to a procedure of careful accounting at a level that is billions of times larger than 1950’s age experiments

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Upper Limits on the Neutrino Mass from the Tritium Beta Spectrum*

DONALD R. HAMILTON, W. PARKER ALFORD,† AND LEONARD GROSS‡
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received August 25, 1953)

The shape of the tritium beta spectrum near the end point has been investigated in a spherical electrostatic integral spectrograph with particular reference to the possible effects of a nonzero neutrino mass. It is shown that the source thickness of 100 micrograms/cm² may be satisfactorily taken into account in the last kilovolt of the spectrum, upon which the results are based. An upper limit to the neutrino mass of 500, 250, and 150 electron volts is found for the Dirac, Majorana, and Fermi forms, respectively, of the beta interaction.

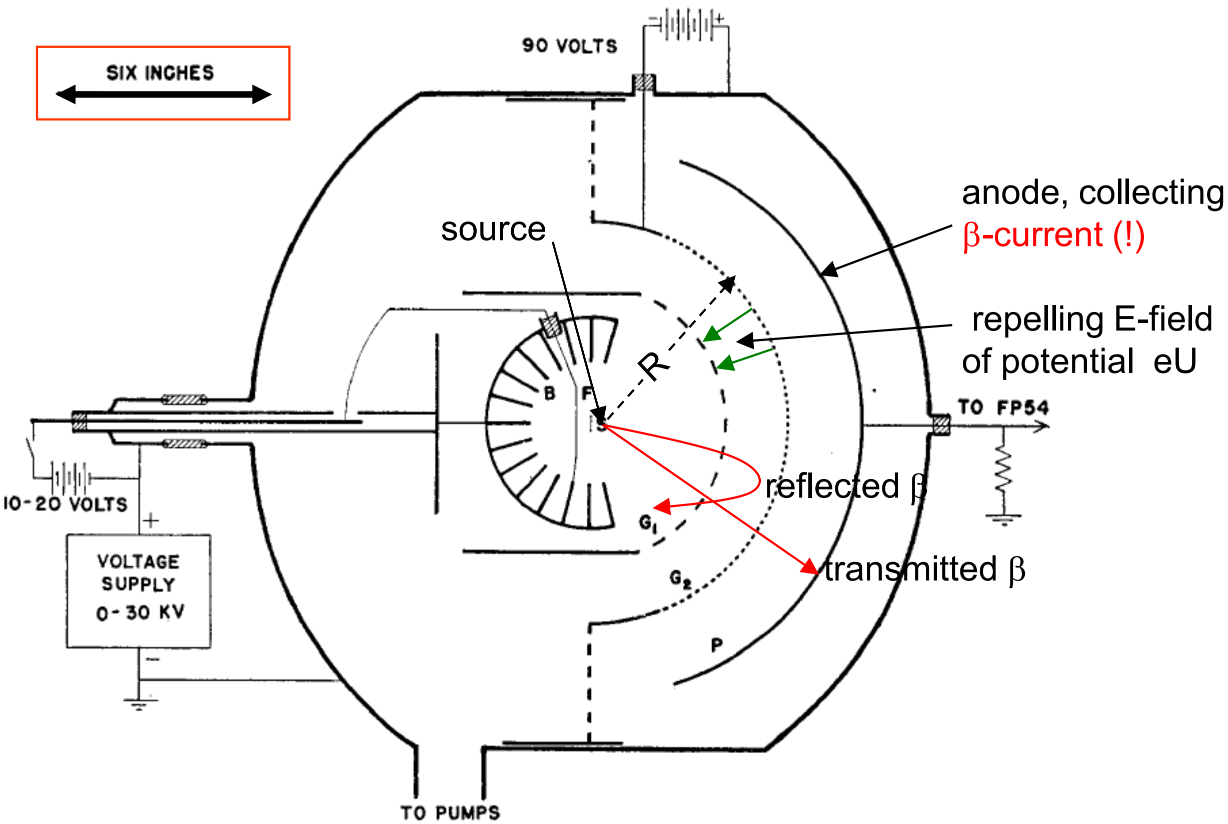


FIG. 1. Schematic diagram of electrostatic beta-spectrograph showing collector P, grids G_1 and G_2, source S, decharging filament F, and electron backstop B.

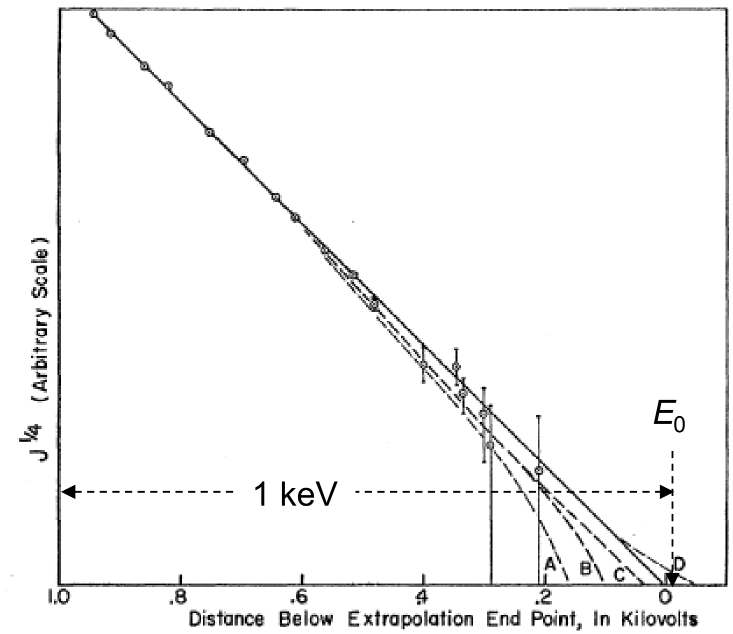


FIG. 3. Fourth root of tritium current plotted against kilovolts below end point. Dotted curves represent curves predicted on the basis of measured resolution and for various neutrino masses and interactions. Majorana, Fermi, and Dirac interactions indicated by (0) (+) (−), respectively. Neutrino mass μ in electron volts.

Curve A: $\mu=250$ (+), 350 (0).
Curve B: $\mu=150$ (+), 200 (0).
Curve C: $\mu=500$ (−).
Curve D: $\mu=0$ (0, +, −).

PTOLEMY Project

- Starting a new project is hard to do…
  – Relic neutrinos, however, have such a strong physics case that many physicists believe that this is the time
- The Simons Foundation has funded a proof of concept detector
  – We believe that a rich physics program can already begin with the as-built PTOLEMY project
  – 1st Relic Neutrino Direct Limits, Joint X-Ray Astro – keV Sterile Neutrino searches, MeV-scale Dark Matter and low energy Solar neutrino scattering spectra – and more theory on potential CNB anisotropies

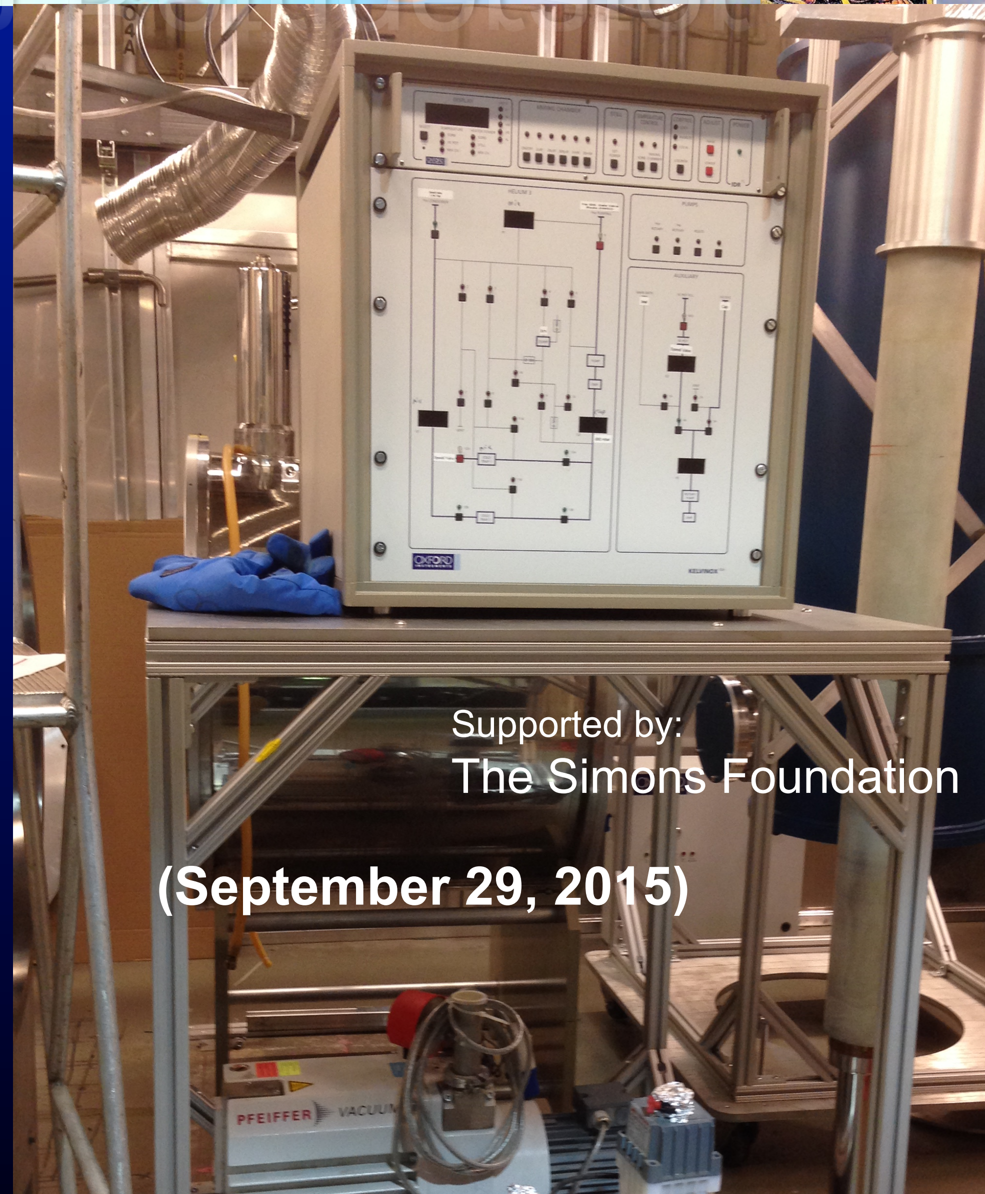
PTOLEMY MAC-E Filter

Side View
(PPPL)

Supported by:
The Simons Foundation

End-on-View (May 11, 2015)

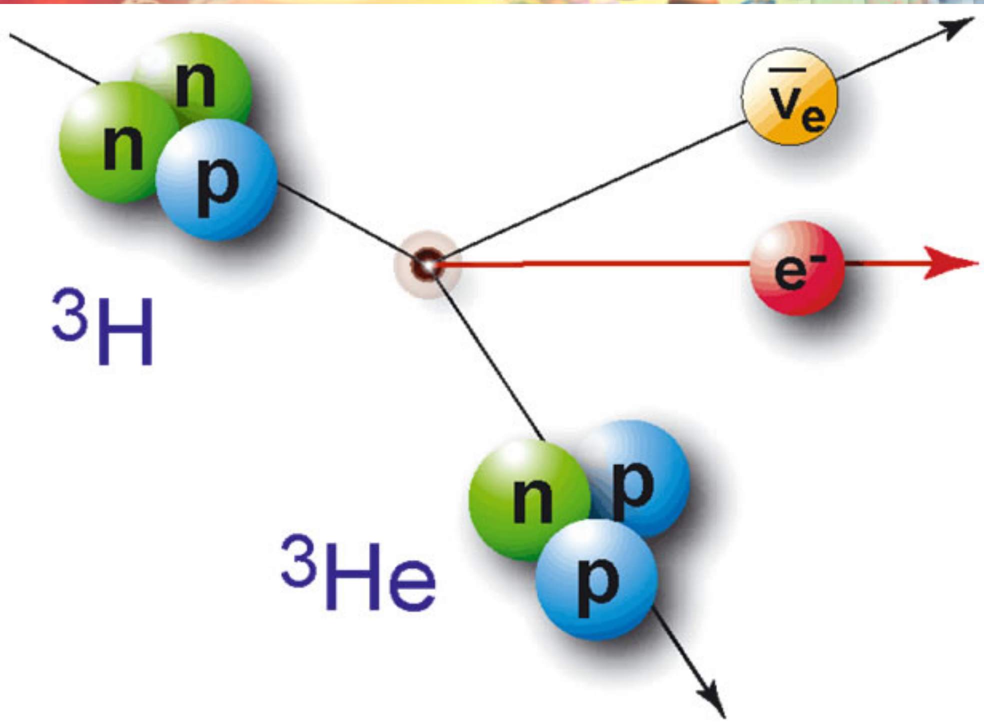
PTOLEMY Dilution Refrigerator



Supported by:
The Simons Foundation

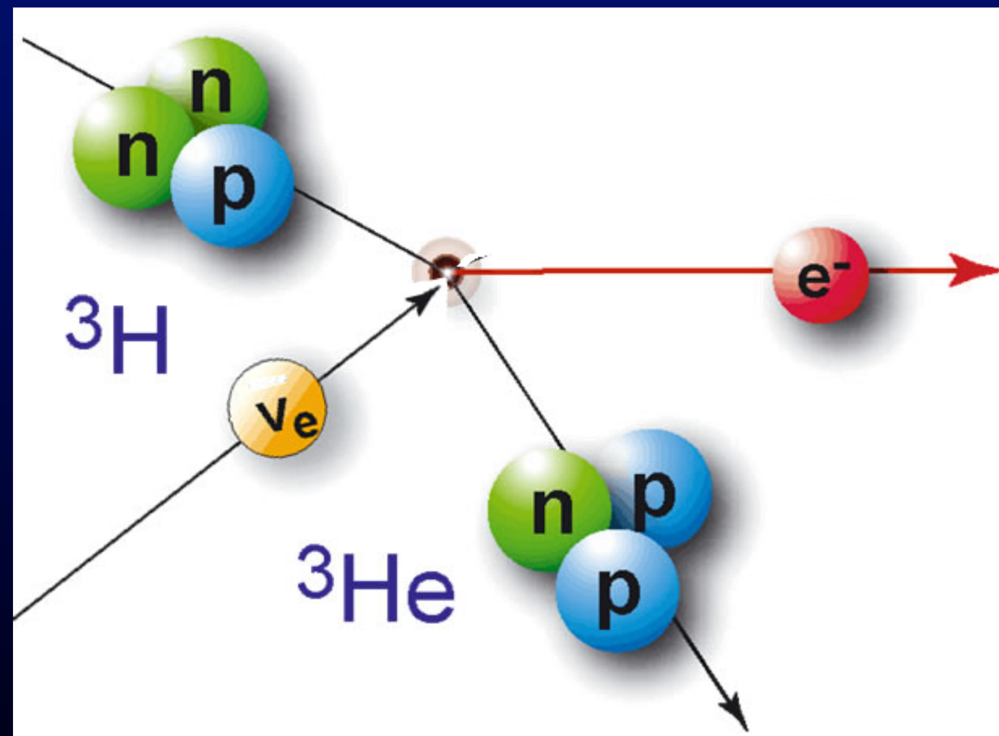
(September 29, 2015)

Tritium



Tritium β-decay
(12.3 yr half-life)

Neutrino capture on Tritium



Relic Neutrino Detection

- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in 1962 [*Phys. Rev.* 128:3, 1457]
  - Look for relic neutrino capture on tritium by measuring electrons at or above the endpoint spectrum of tritium beta-decay

What do we know?

Gap (2m) constrained to < ~0.6eV from Cosmology

(some electron flavor expected with 2m>0.1eV from neutrino oscillations)

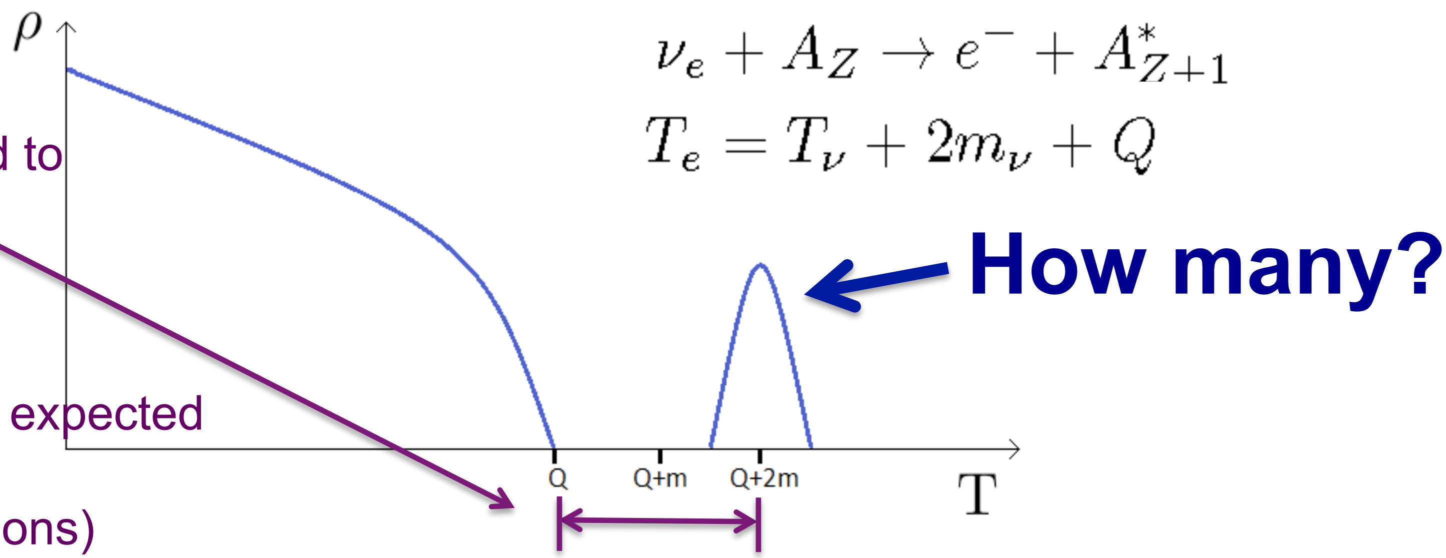
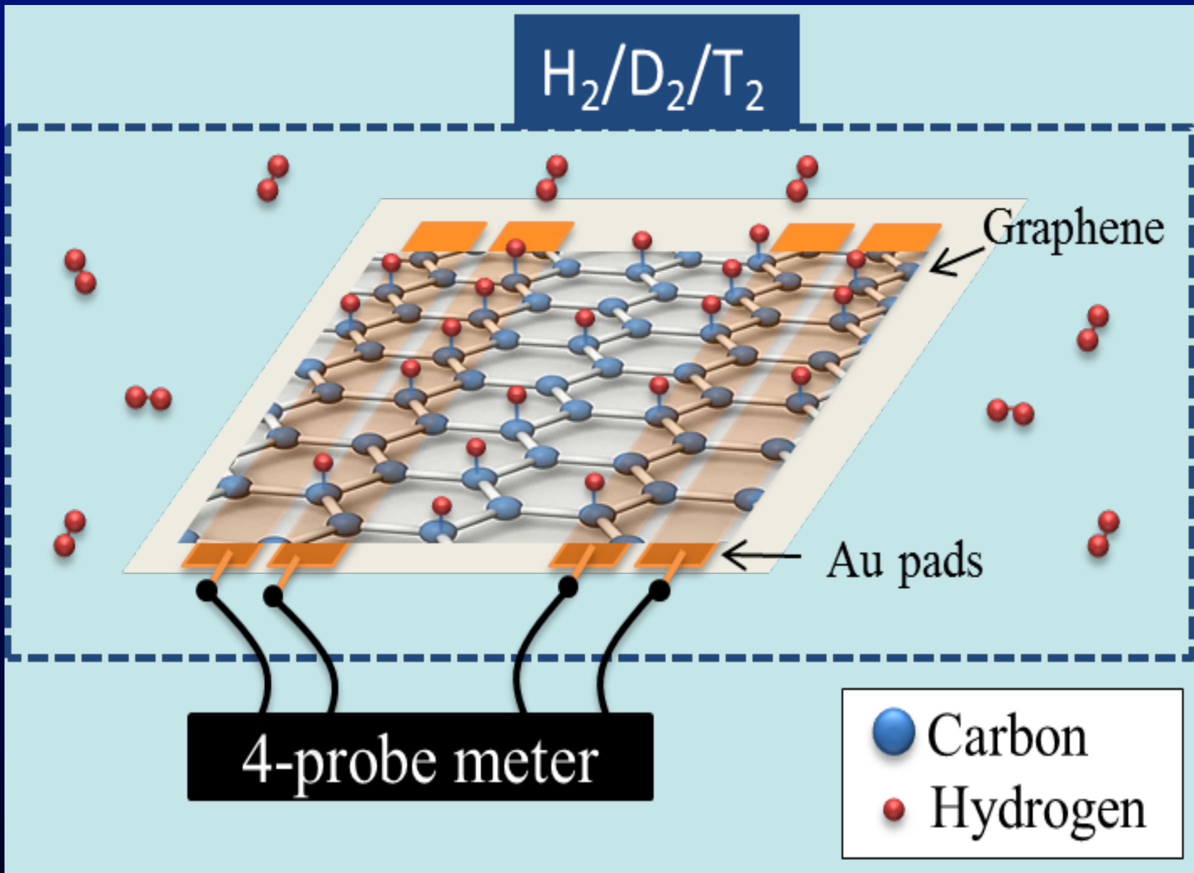


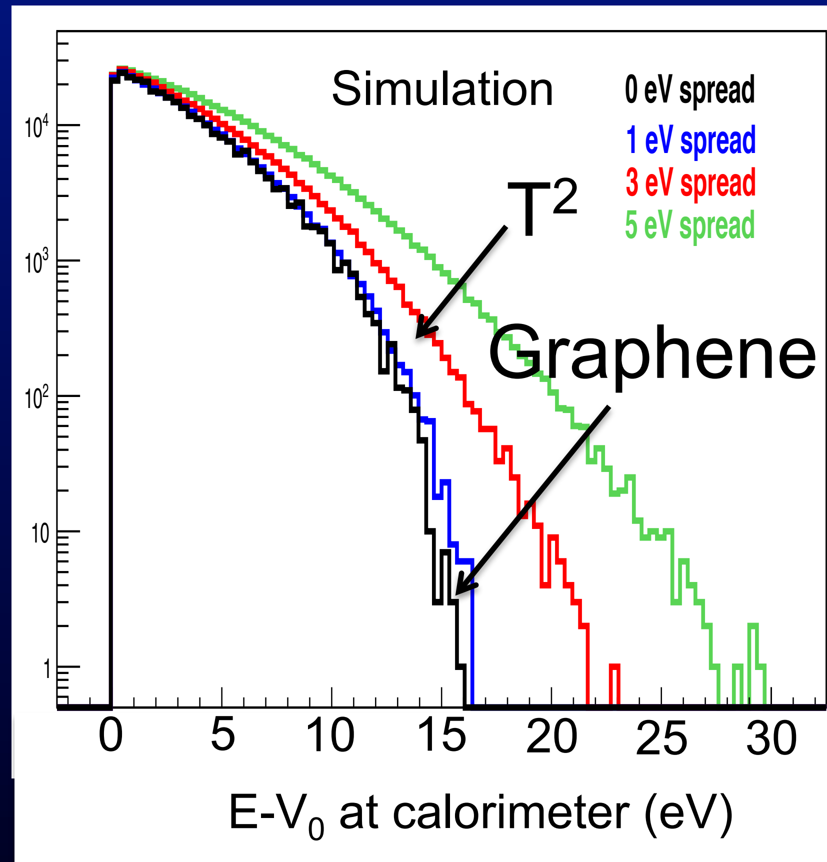
Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

Tritium and other isotopes studied for relic neutrino capture in this paper: JCAP 0706 (2007)015, hep-ph/0703075 by Cocco, Mangano, Messina

Tritium-loaded Graphene

First Samples from SRNL expected in December 2015





Relic Neutrino Capture Rates

- Target mass: **100 grams of tritium** (2×10^{25} nuclei)
- Capture cross section * (v/c) ~ 10^{-44} cm^2 (flat up to 10 keV)
- (Very Rough) Estimate of Relic Neutrino Capture Rate:

($56\ \nu_e$/cm^3) (2×10^{25} nuclei) (10^{-44} cm^2) (3×10^{10} cm/s) (3×10^7 s)

Lazauskas, Vogel, Volpe: J.Phys.G G35 (2008) 025001.
Cocco, Mangano, Messina: JCAP 0706 (2007) 015

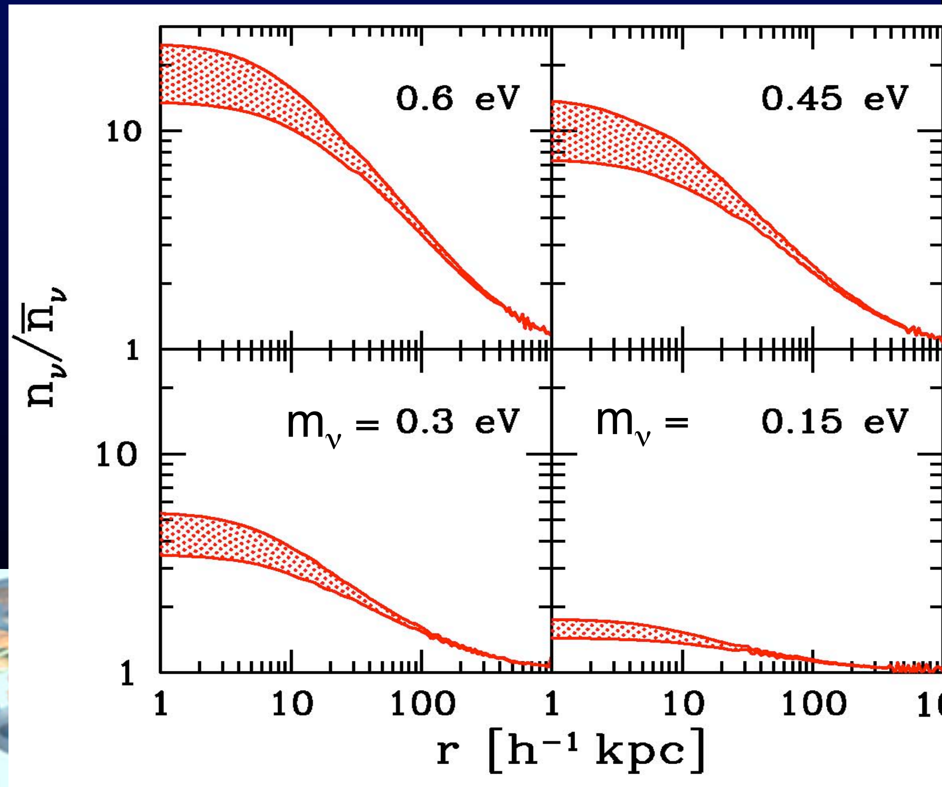
~ 10 events/yr

(5 events/yr for Dirac neutrinos)

$\sigma(v/c) = (7.84 \pm 0.03) \times 10^{-45}$ cm^2

Known to better than 0.5%

Gravitational clumping could potentially increase the local number of relic neutrinos.
For low masses ~0.15eV, the local enhancement is ~x1.5



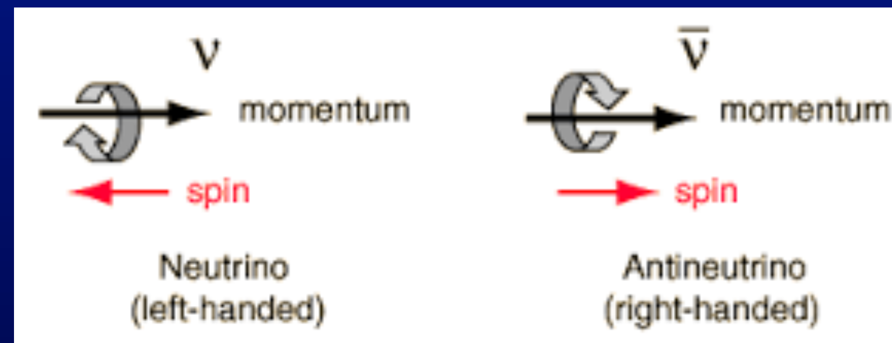
Ringwald and Wong (2004)

Dirac versus Majorana Neutrinos

Relic neutrinos are uniquely the largest source of non-relativistic neutrinos

Long, Lunardini, Sabancilar: arXiv:1405.7654

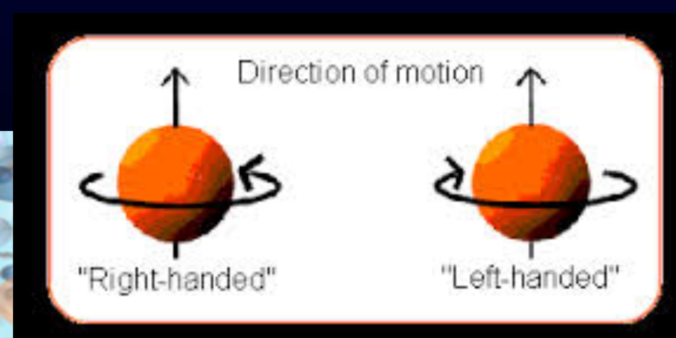
Factor of 2 difference in capture rate



- Neutrinos decouple at relativistic energies
- Helicity (not chirality) is conserved as the universe expands and the relic neutrinos become non-relativistic

Dirac: after expansion, only ~half of left-handed helical Dirac neutrinos are left-handed chiral (active) and antineutrinos are not captured

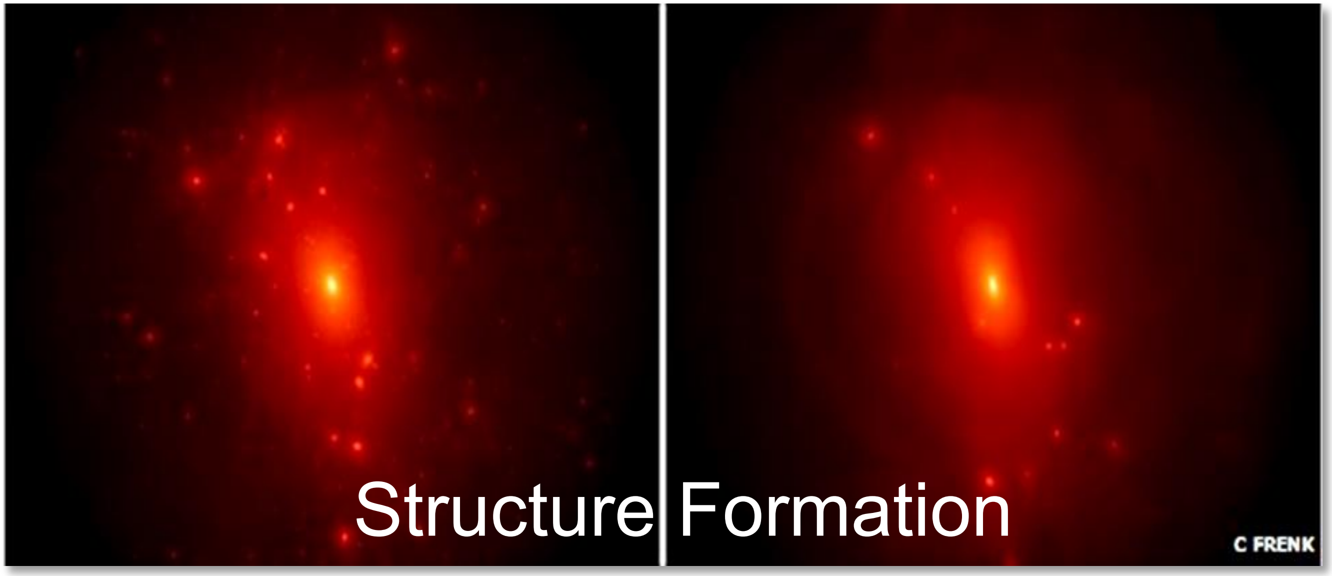
Majorana: ~half of left-handed helical neutrinos are chiral left-handed and half of right-handed helical neutrinos are chiral left-handed (active)



If neutrinos are Majorana, lepton number is not conserved → Leptogenesis

Sterile Neutrinos

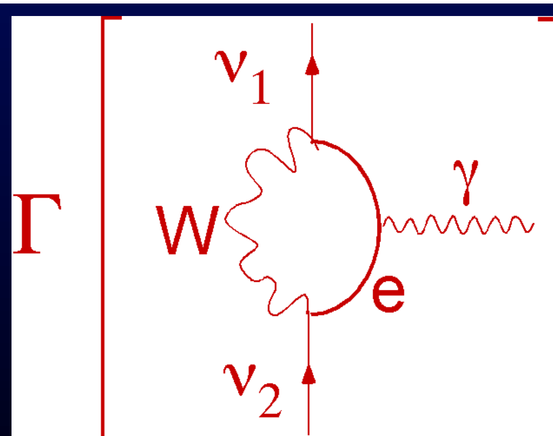
CDM simulations WDM

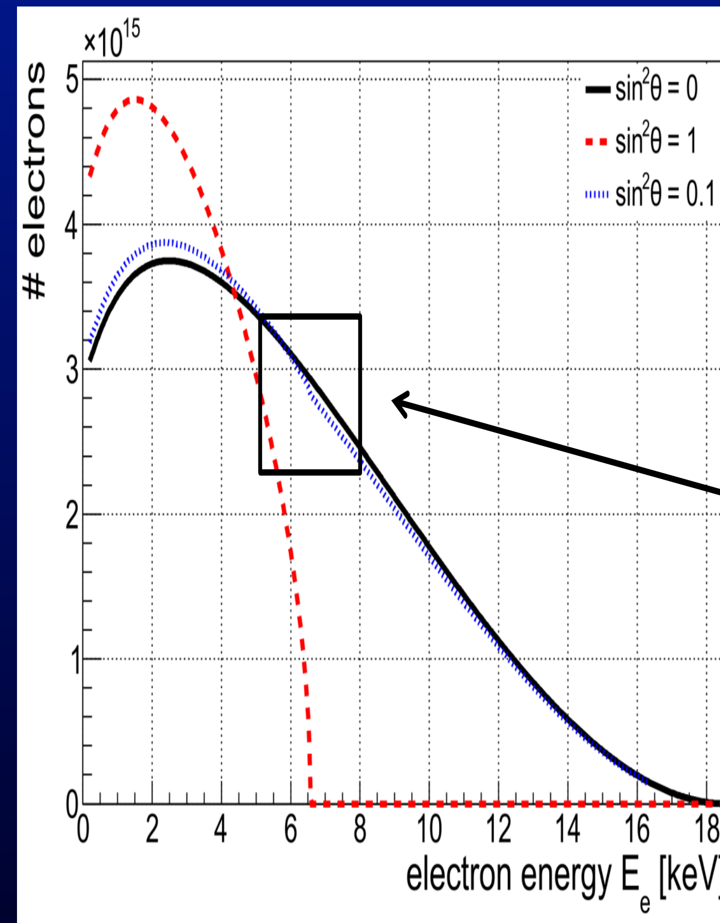


X-Ray Astronomy

$\nu_2 \rightarrow \nu_1 + \gamma$

$\propto G_F^2[m(\nu_2)]^5$





Kai Dolde (Meudon 2014)
Susanne Meurtens (KATRIN)

Sterile neutrinos will introduce a kink in the beta-decay spectrum at $K^0_{end} - m_4$ where sensitivities down to $|U_{e4}|^2 \sim 10^{-8}$ may be possible.

Relevant Parameter Space

Sterile neutrino (inverse) lifetime

$$\frac{1}{\tau} = (6 \times 10^{-33}\mathrm{s}^{-1}) \left[\frac{\sin^2(2\theta)}{10^{-10}}\right] \left[\frac{m_s}{\mathrm{keV}}\right]^5$$

10 keV:

$\sin^2(2\theta) \sim 10^{-2}$ (~ age of universe)

→ WDM overdensity

$\sin^2(2\theta) \sim 10^{-5}$

→ Too bright

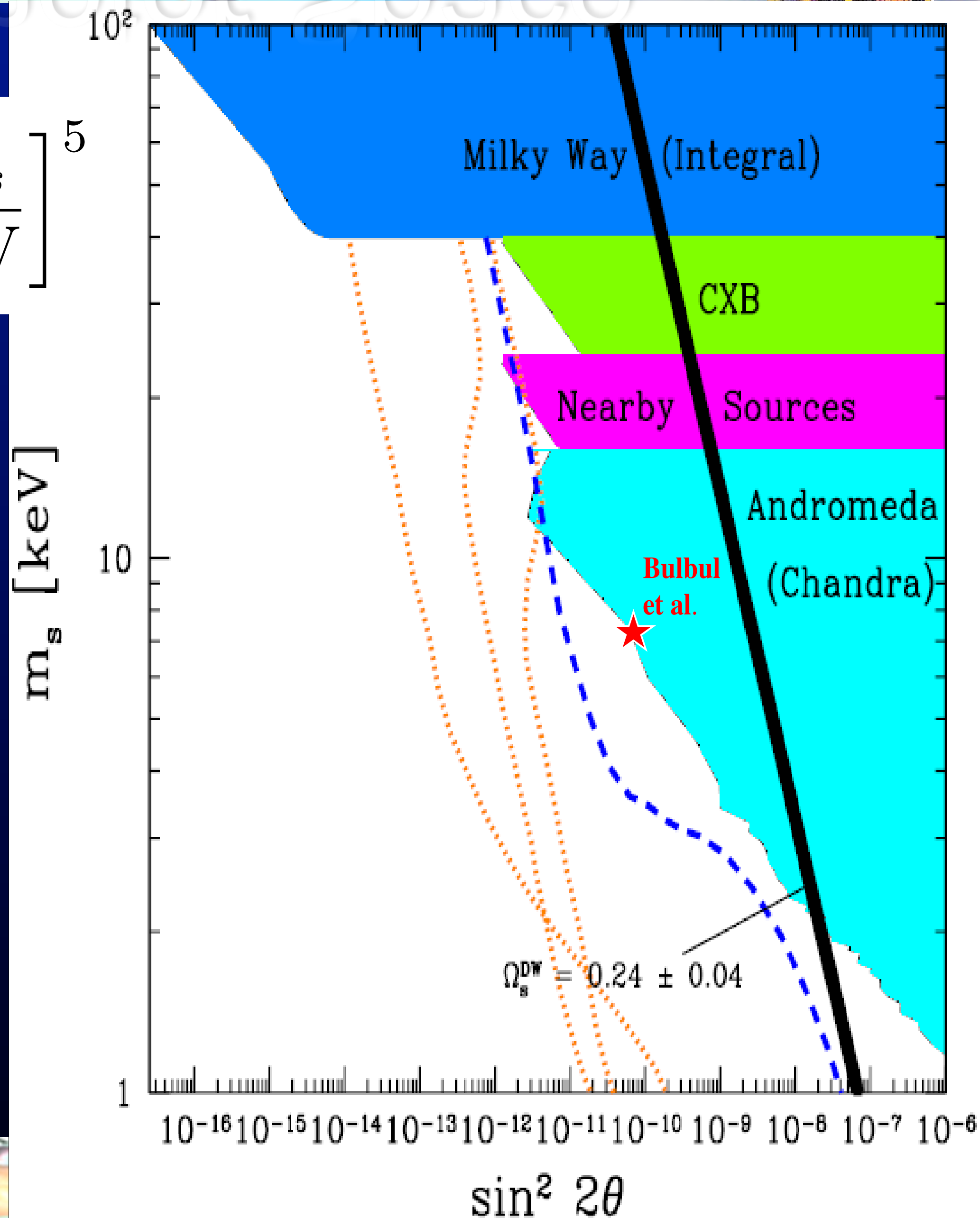
$\sin^2(2\theta) <\sim 10^{-11}$

→ Dim enough to be (yet) undiscovered

7 keV: $\sin^2(2\theta) <\sim 10^{-10}$

4 keV: $\sin^2(2\theta) <\sim 10^{-9}$

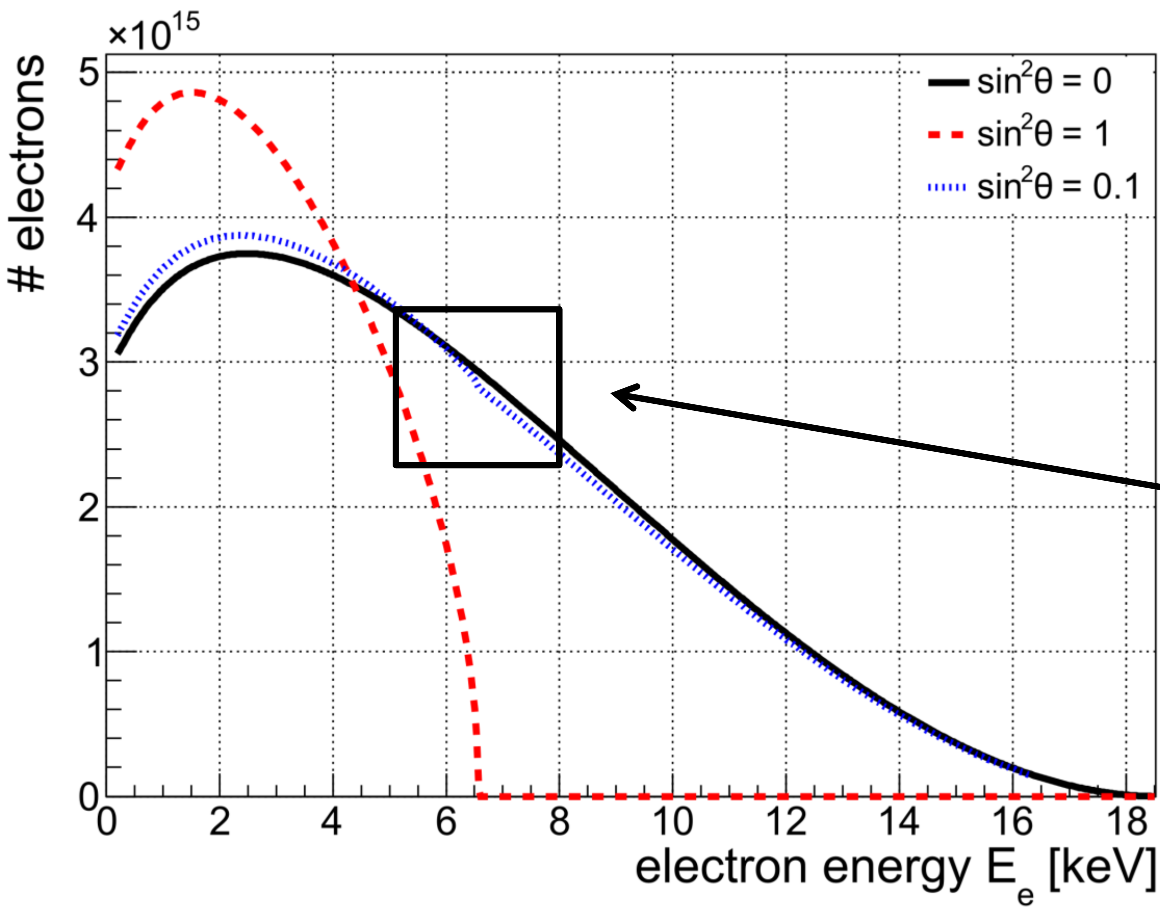
2.5 keV: $\sin^2(2\theta) <\sim 10^{-8}$



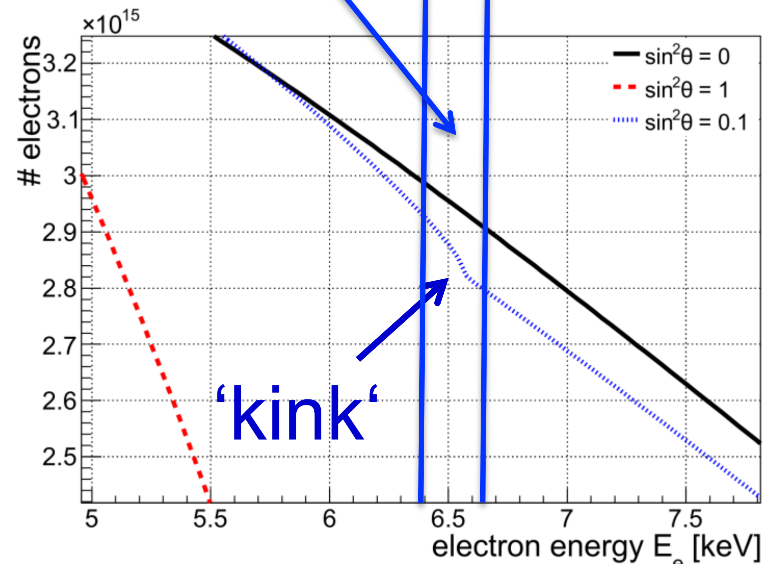
Sterile Neutrino Kink Finding

Mixing of keV-neutrinos and light neutrinos with mixing angle θ:

$$\frac{d\Gamma}{dE_e} = \sin^2\theta \left(\frac{d\Gamma}{dE_e}\right)_{m_{heavy}} + \cos^2\theta \left(\frac{d\Gamma}{dE_e}\right)_{m_{light}}$$

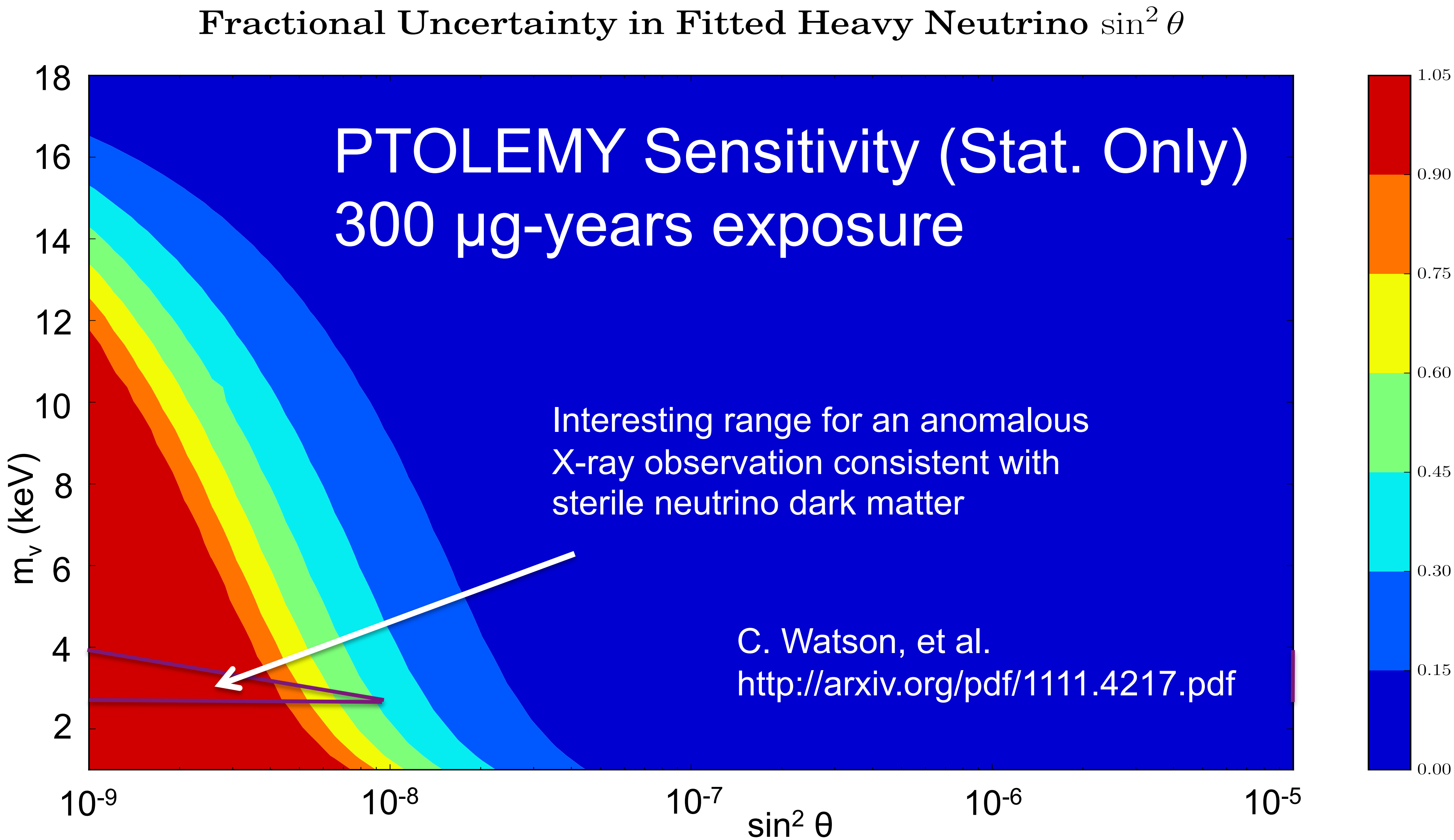


PTOLEMY "narrow window" search concept



Kai Dolde (Meudon 2014)
Susanne Meurtens (KATRIN)

Sensitivity Scan

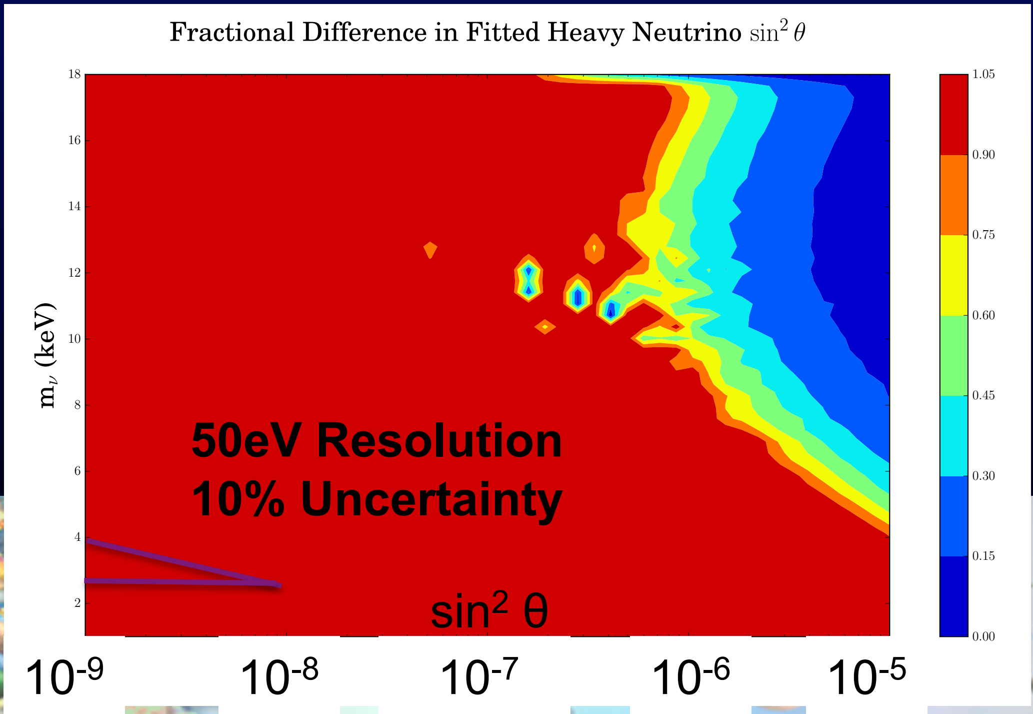


Limiting Systematics

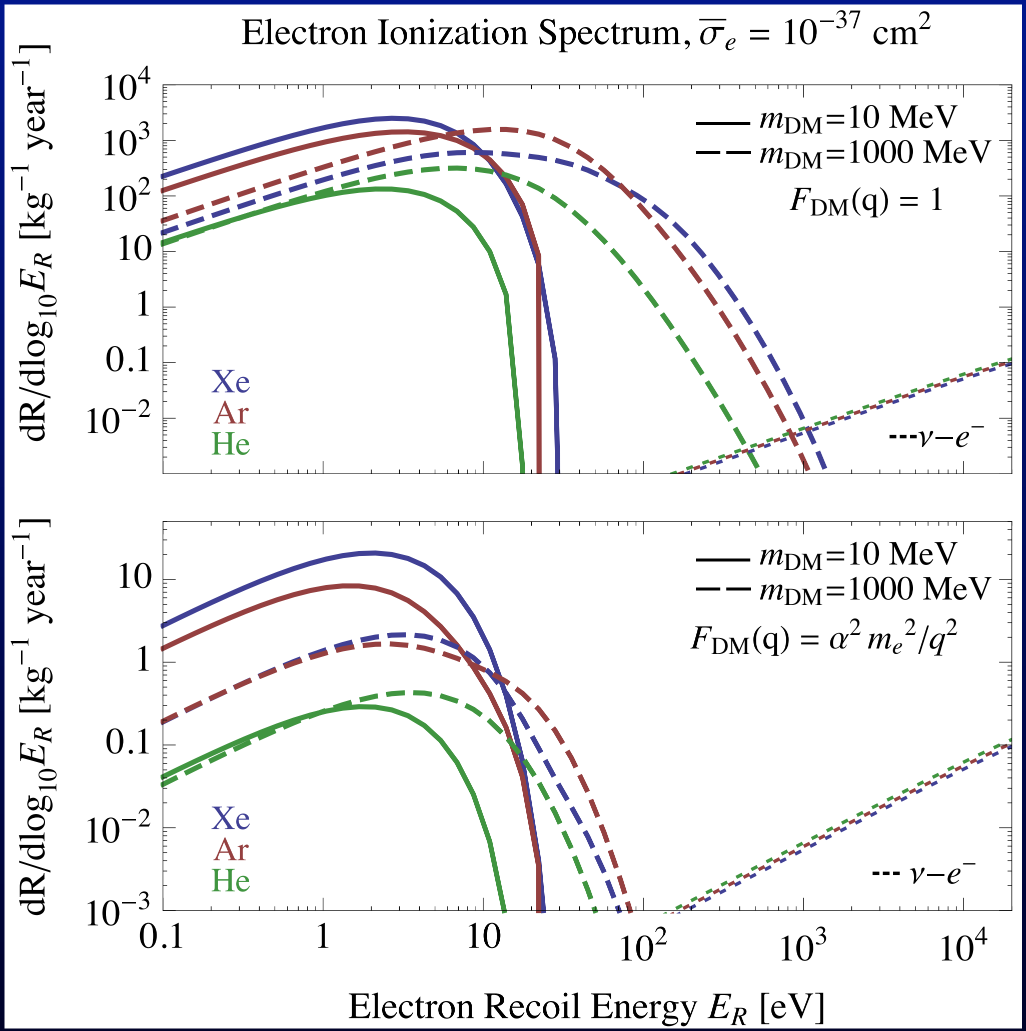
- Expected versus Observed Calorimeter Resolution
  - Single most important systematic:

    Energy Resolution Uncertainty
  - Scanning Base Calorimeter Resolution from 0.1eV to 50eV and fitting with the correct resolution had less effect than using 50eV resolution and applying a 10% shift up and down in the fit

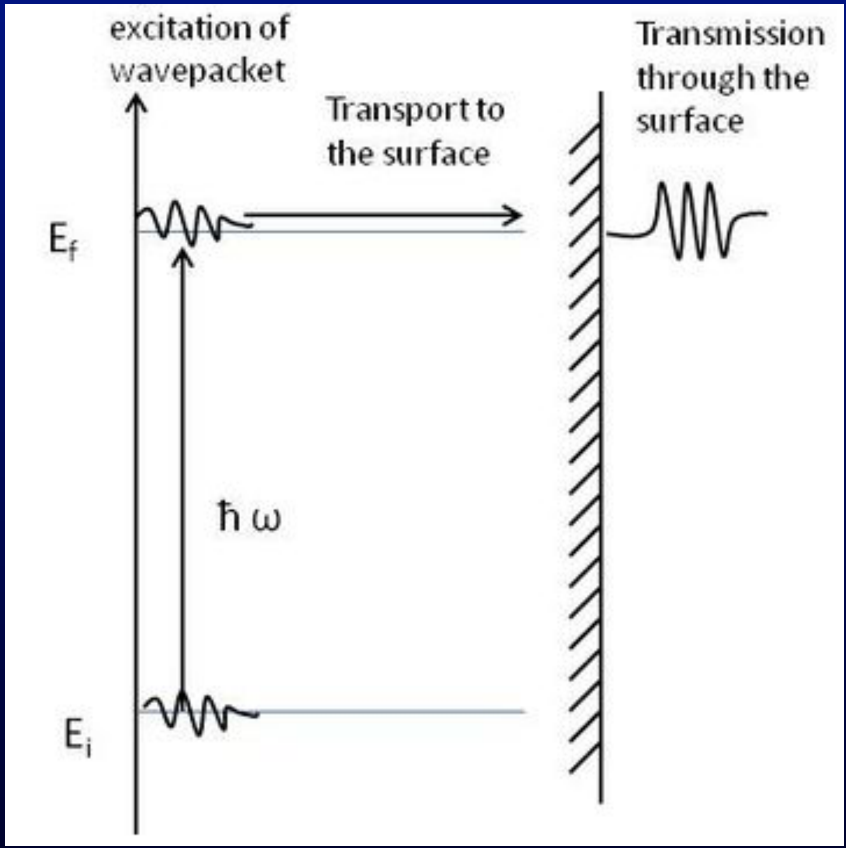
Sensitivity completely lost



MeV-scale Dark Matter



Photocathode or Biased-Diamond at MAC-E mid-plane (no step-down)

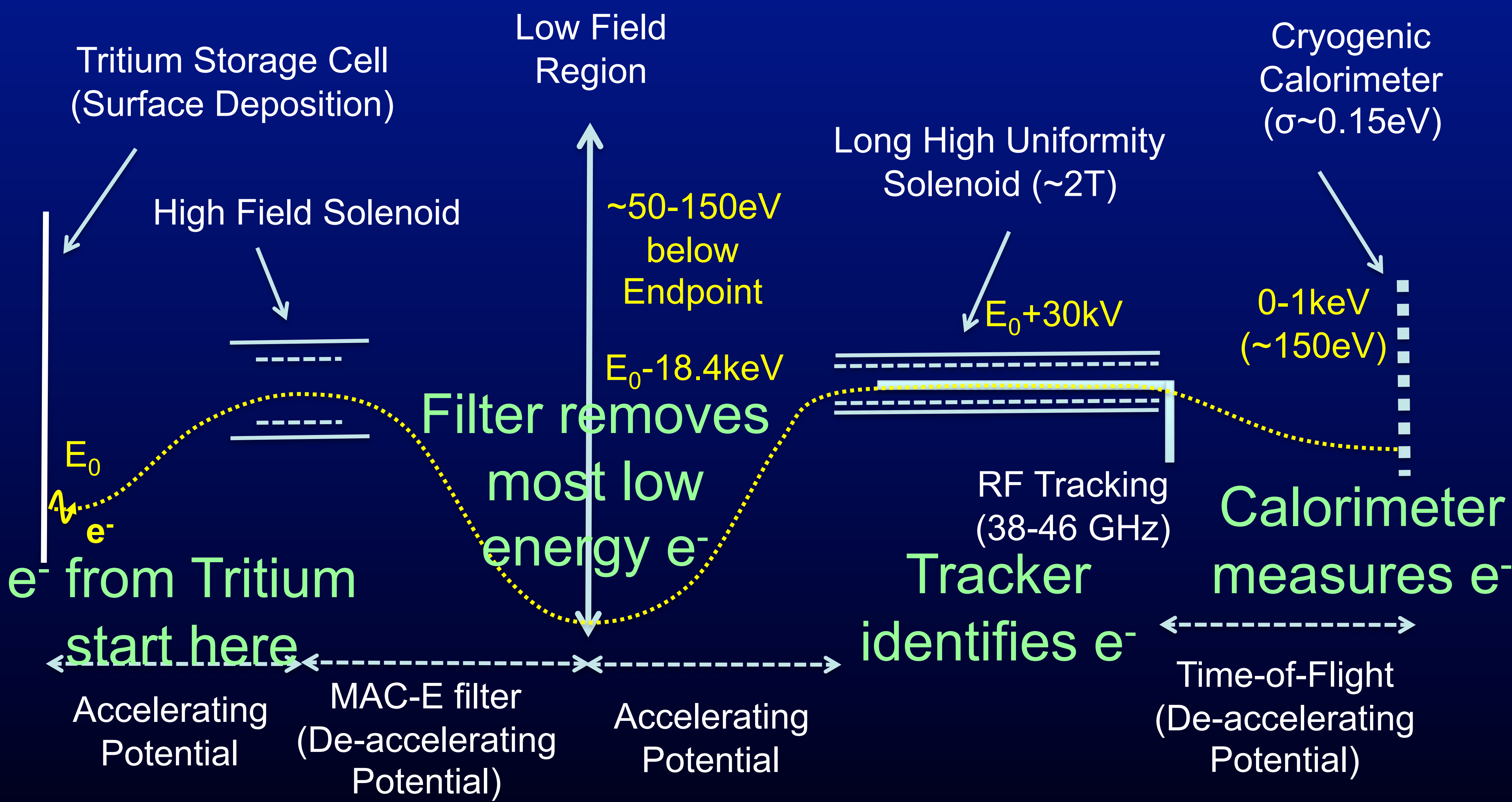


R. Essig, J. Mardon, and T. Volansky, *Direct detection of sub-GeV dark matter*, Physical Review D **85**, 076007 (2012).

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, *First direct detection limits on sub-GeV dark matter from XENON10*, Physical review letters **109**, 021301 (2012).

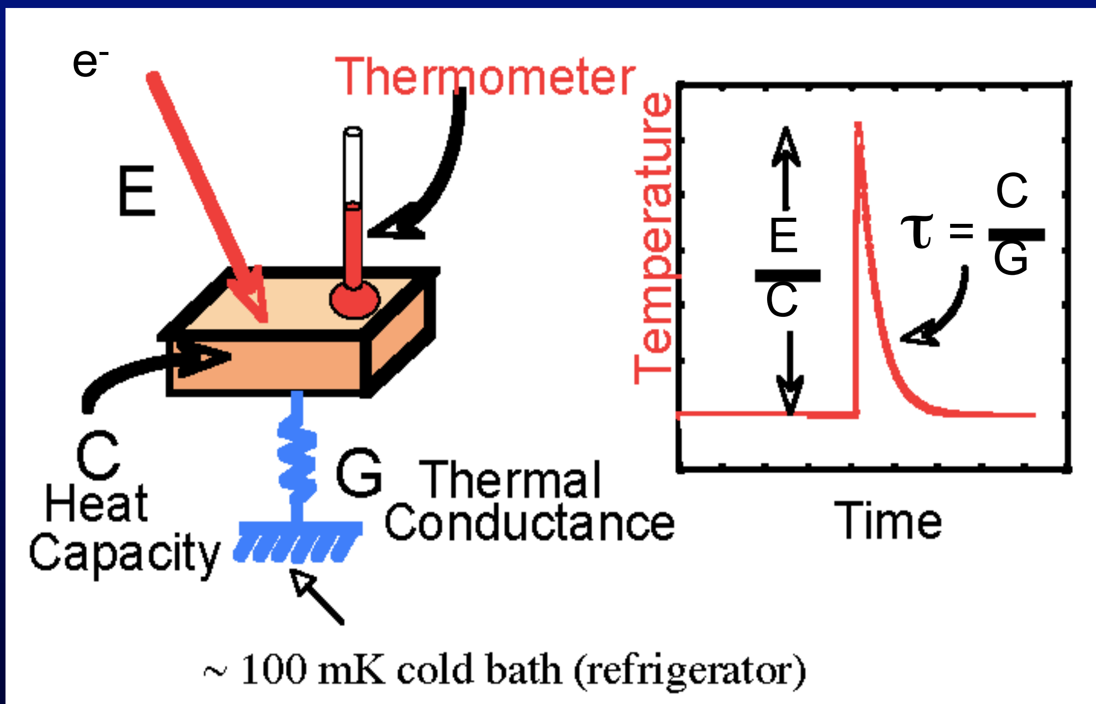
PTOLEMY Experimental Layout

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield



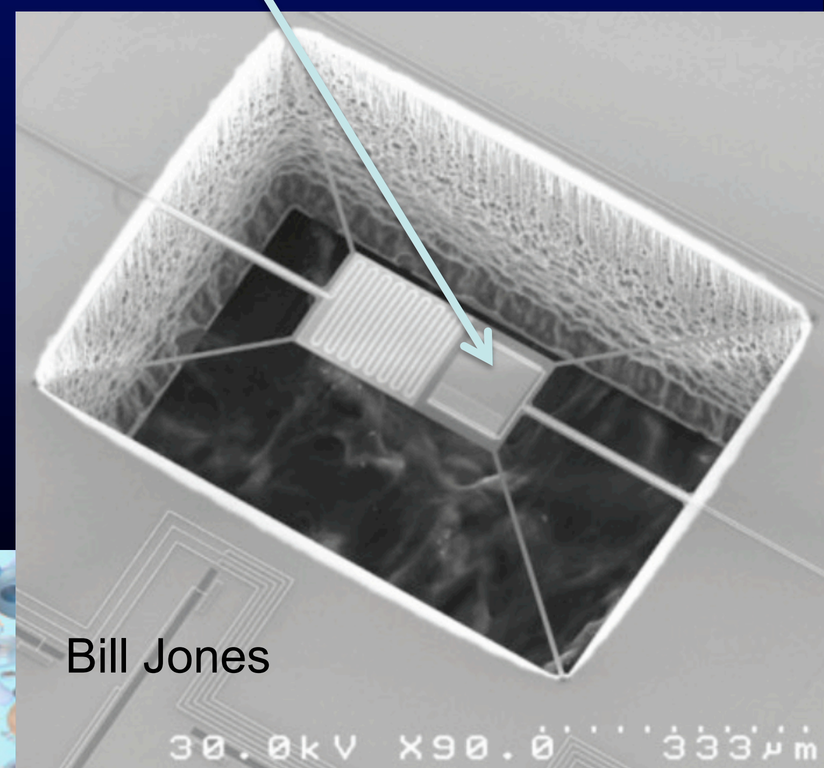
Transition-Edge Sensors for Calorimetry

– ANL Group (Clarence Chang) estimates ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK



100eV electron can be stopped with very small C

(example) SPIDER Island TES



Bandwidths of ~1 MHz to record ~10kHz of electrons hitting the individual sensors

Calorimeter Energy Resolution

$$\Delta E_{\mathrm{FWHM}} = 2.355\sqrt{(4k_b T_c^2 C/\alpha)}\sqrt{(1+M^2)n/2}$$

Applied Physics Letters **87, 194103 (2005);**
doi: 10.1063/1.2061865

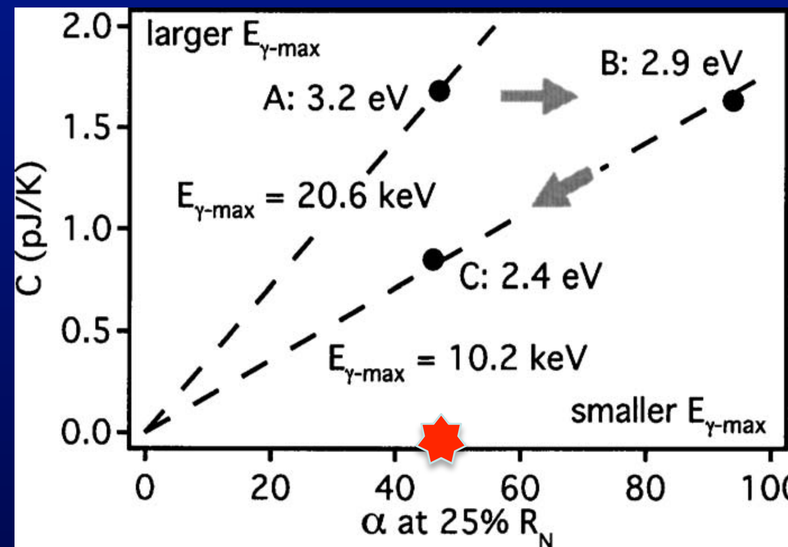
(C/α) scaled down by a factor of 100

Keep α large, keep M small

Clarence Chang

Electron energy at calorimeter:	Thickness of Gold Absorber:
100 eV	**2.39 nm**
10 eV	**0.68 nm**

X-Ray are typically 15 μm

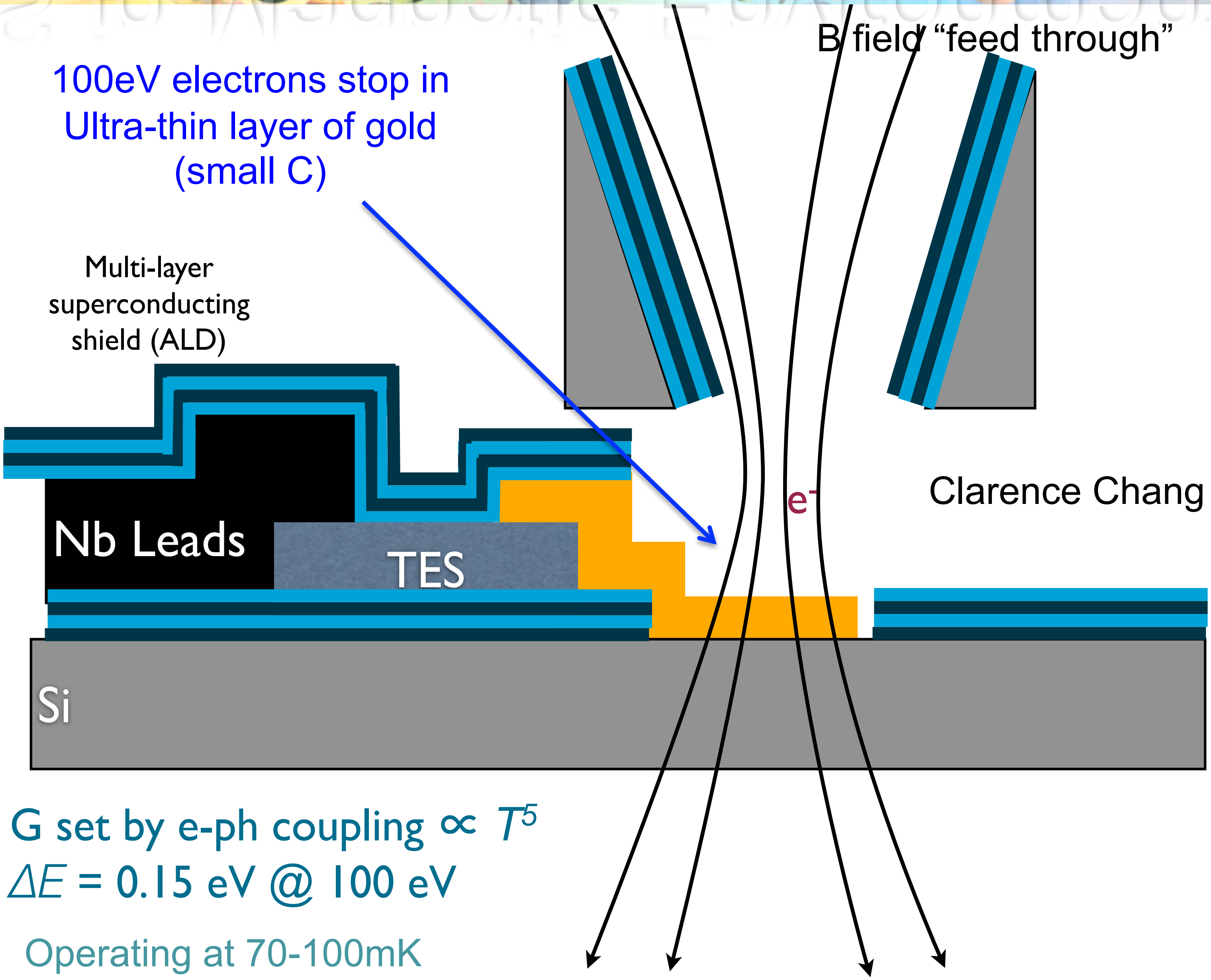


$$\alpha \propto \frac{1}{\Delta T_{width}}$$

- Thickness of Gold absorber can be 5 nm (~40 atomic layers), corresponding to C_p of approximately 0.04 pJ/K per mm^2
- Transition-edge steepness (1/α) controlled by normal regions and magnetic field.

Important collaboration with balloon and space-based TES that want to develop more effective/active magnetic shielding/compensation (Goddard GFSC – John Sadleir, Harvey Moseley, Elmer Sharp, Simon Bandler, Stephen Smith)

TES in Magnetic Environment



G set by e-ph coupling ∝ T^5

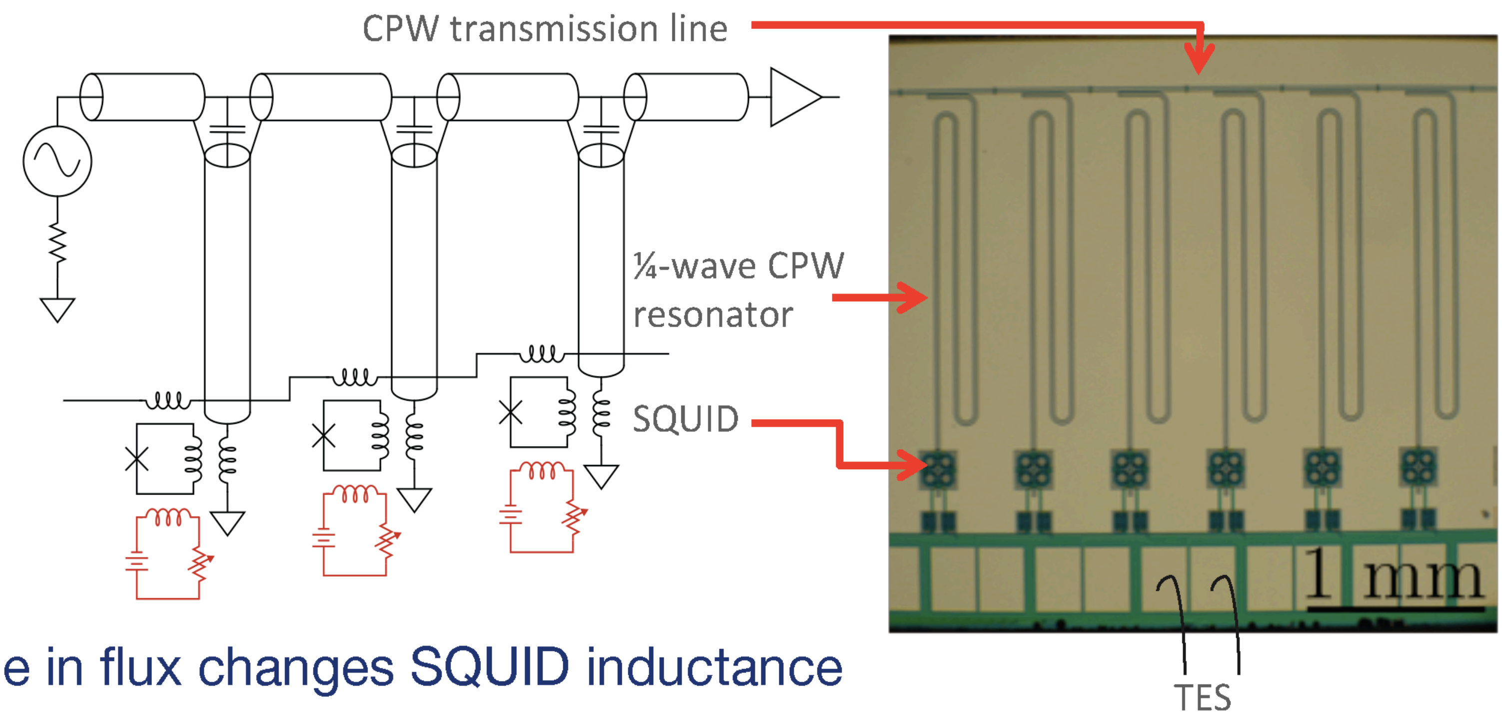
ΔE = 0.15 eV @ 100 eV

Operating at 70-100mK

R&D on Magnetic Shielding has important overlap with TES operational parameters for a wide number of land, balloon and space-based microwave and X-ray telescopes (working with Jack Sadleir, Harvey Moseley, Elmer Sharp and others at Goddard GSFC)

Highly Multiplexed SQUID Readout

Microwave-readout Massive SQUID Multiplexer



- Change in flux changes SQUID inductance
- at 1-10 GHz, can support ~1 MHz of bandwidth with ~1000 channels per line
- Originally developed for CMB measurements, recently demonstrated successful operation with X-ray u-cals

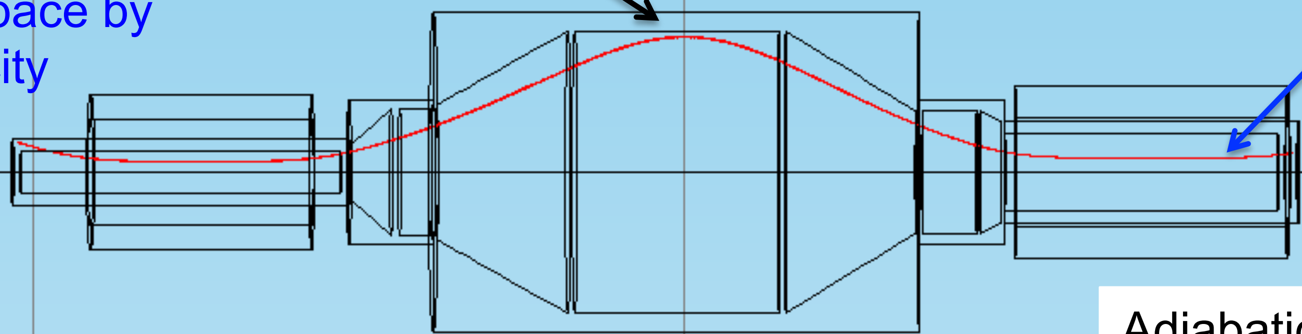
Kent Irwin

PTOLEMY MAC-E Filter

ExB drift before entering MAC-E filter
- Can be used to differentiate electron phase space by longitudinal velocity

Limiting electron trajectory (hits outer radius of filter)

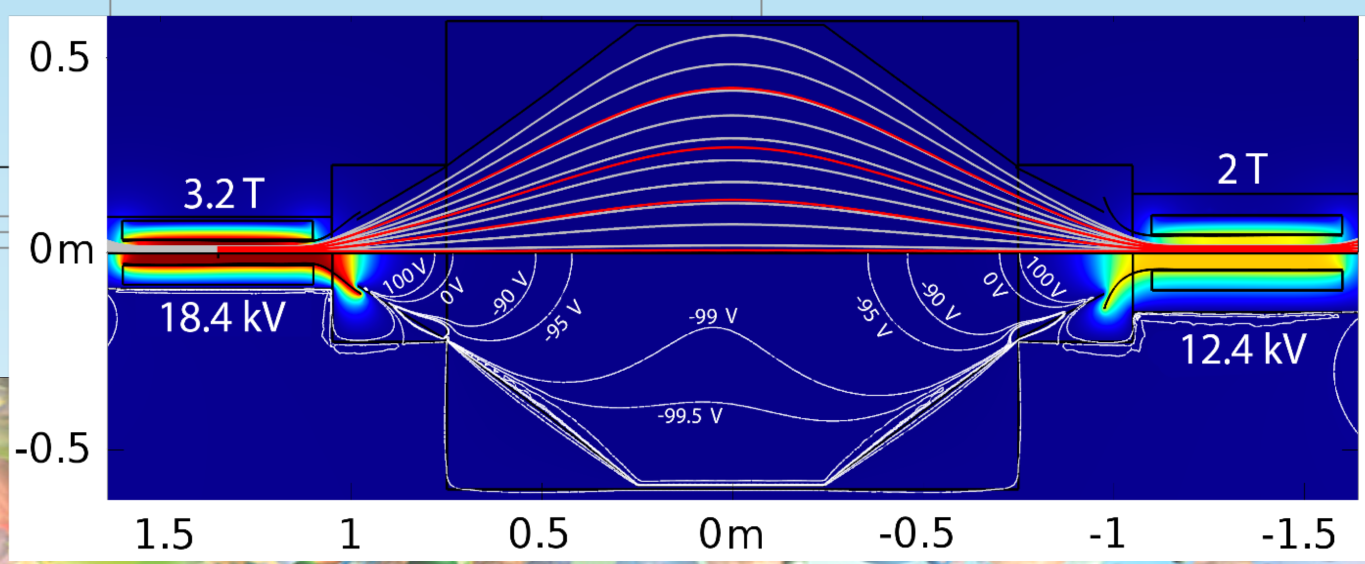
Trajectories can be de-accelerated to have ~constant transit time through RF tracker



Calorimeter

Planar cell aperture of ~30cm^2 within 3.2T bore

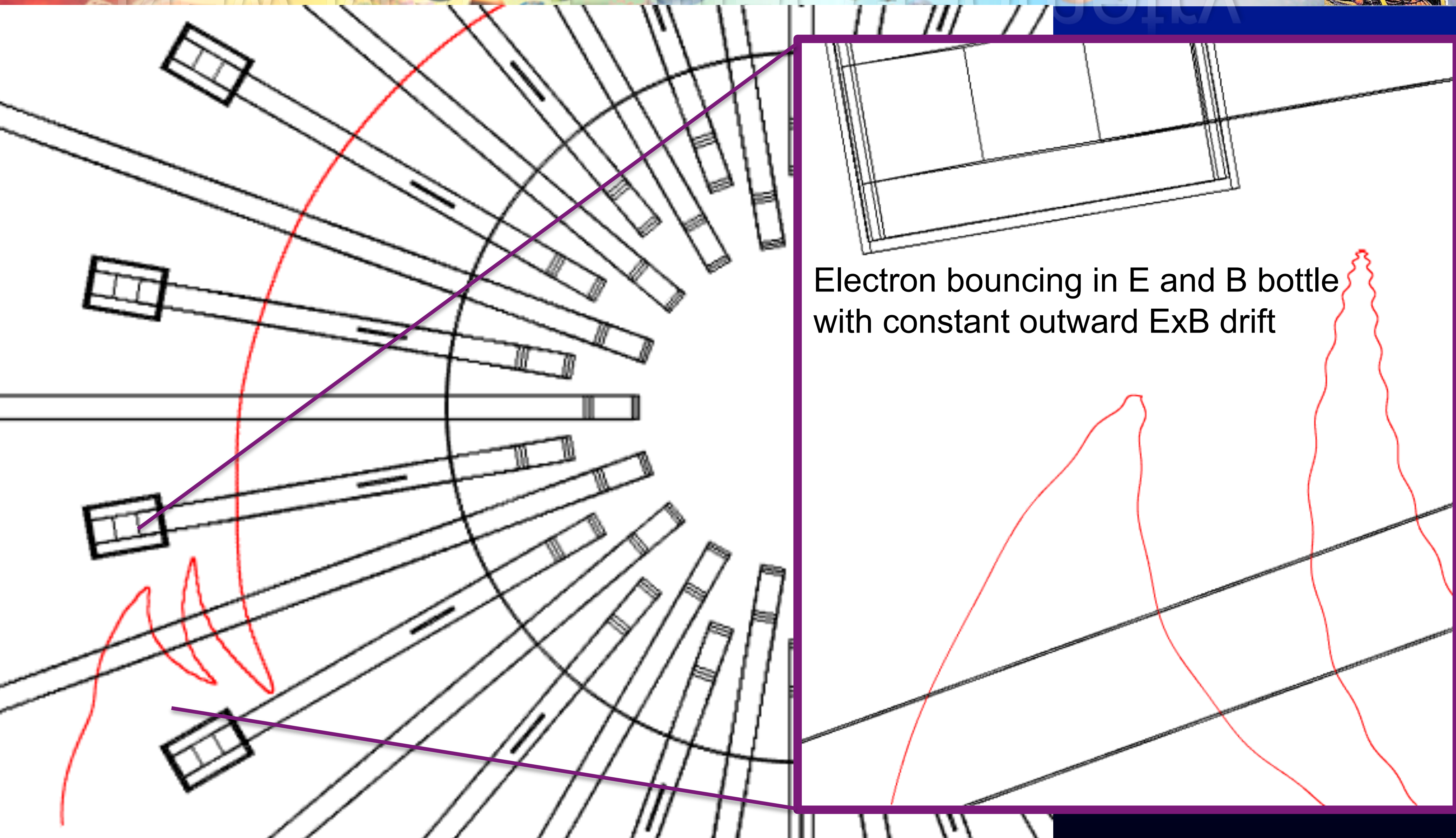
Adiabatic Invariant: $\mu = \frac{E^{\perp}}{B}$



Liouville's Theorem

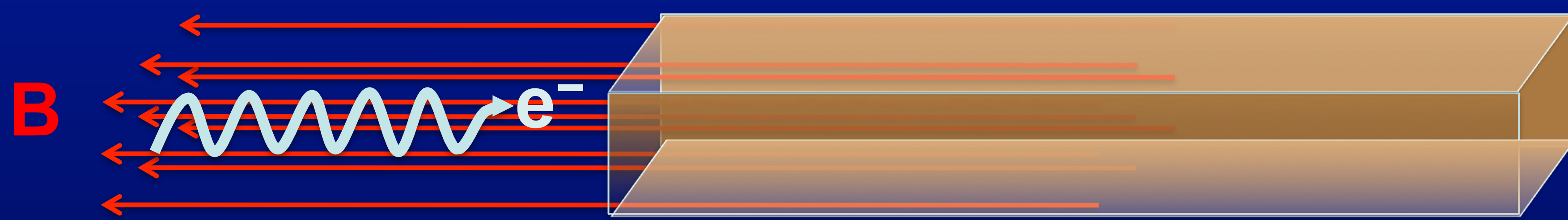
- "Parallel" and "Orthogonal" MAC-E Filters
  - KATRIN $\nabla \vec{B} \parallel \vec{B}$
    - Magnetic flux expands in fringe field between pair of solenoids
    - All electrons pass through one Area aperture
  - PTOLEMY $\nabla \vec{B} \perp \vec{B}$
    - Adiabatic invariant conserved under transverse drift
    - Electrons drift orthogonal to B field under ExB
    - Equivalent Area aperture is replicated many-fold

New MAC-E filter Geometry



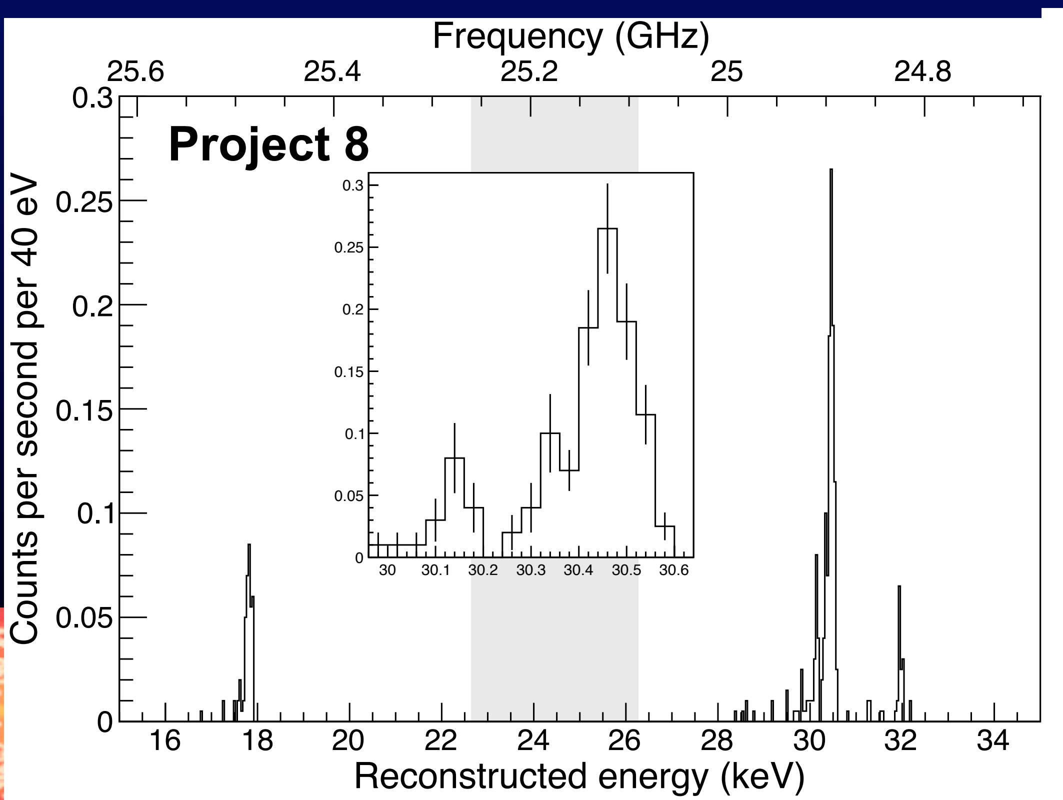
Semi-relativistic Electron Identification

Project 8 has first detection of ~18keV single electron signal!



Asner et al., “Single electron detection and spectroscopy via relativistic cyclotron radiation”, arXiv:1408.5362

- RF tracking (p_T and transit time) and time-of-flight



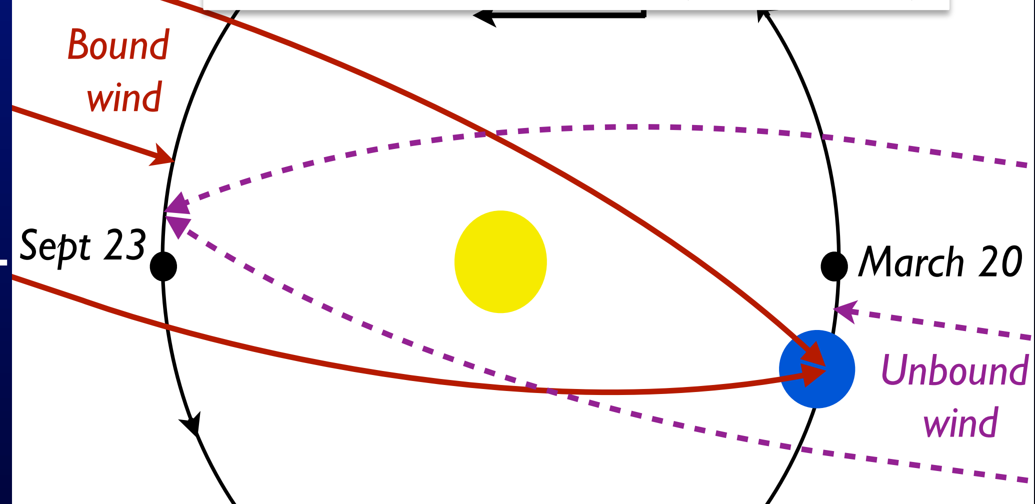
Annual Modulation of Cosmic Relic Neutrinos

B. Safdi, M. Lisanti, et al.
http://arxiv.org/pdf/1404.0680.pdf

Sensitivity to relic neutrino velocity and direction through annual **modulation** amplitude (0.1-1%) and phase
-- Not anytime soon

$$\langle v_{rms} \rangle \propto T/m_\nu \text{ instead of } \propto \sqrt{T/m_\nu}$$

$$\langle v_{rms} \rangle = 160 \text{ km/s} \left(1 \text{ eV}/m_\nu\right)$$

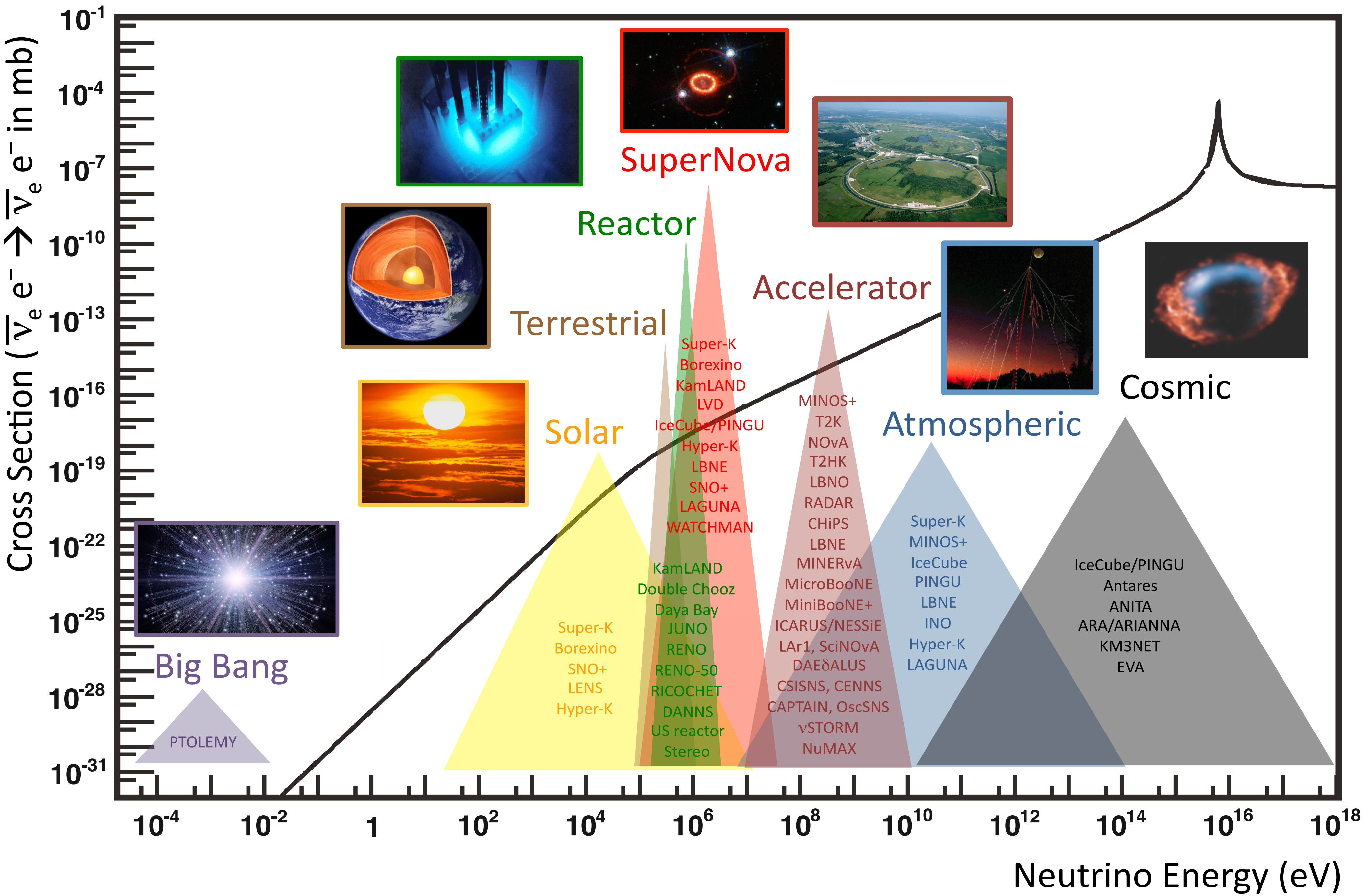


Possible Sensitivity Enhancement:
Polarized Tritium Nucleus
http://arxiv.org/abs/1407.0393 **Safdi, Lisanti, CGT**

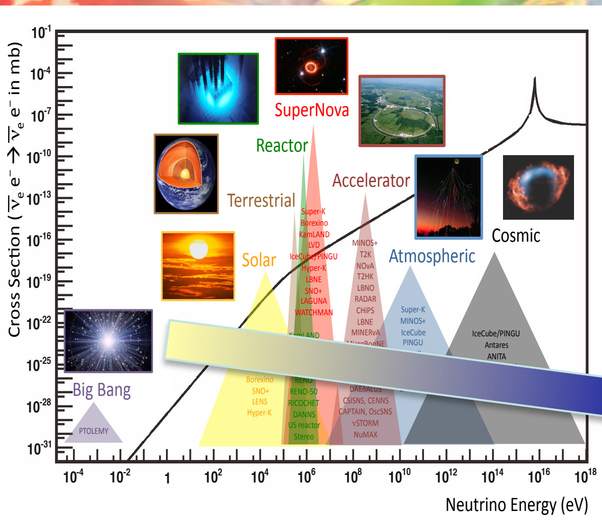
CMB rest frame = Relic Neutrino Rest Frame?

Velocity sensitivity provides possibility to measure:
Relic Neutrino **Rest Frame**, and potentially,
Relic Neutrino **Temperature** (from velocity and mass)
m_ν (lightest) = 0 would contribution to Unbound fraction?

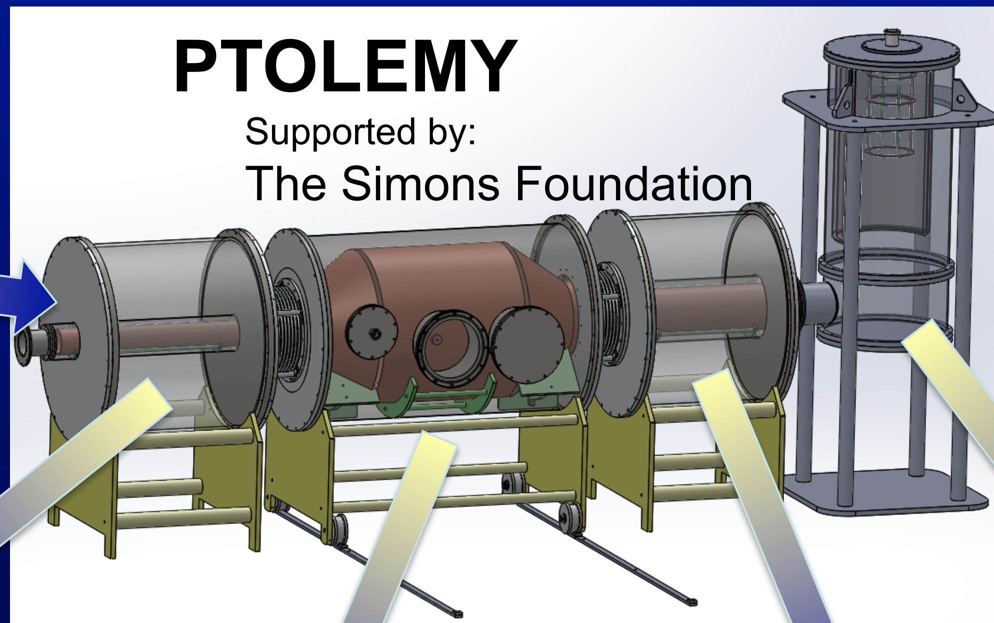
Overview of Neutrino Experiments



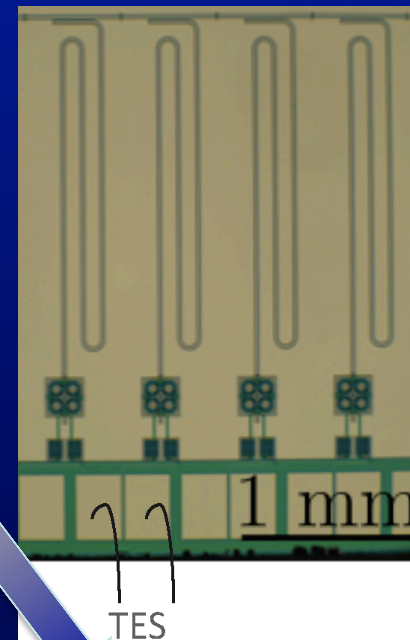
Summary



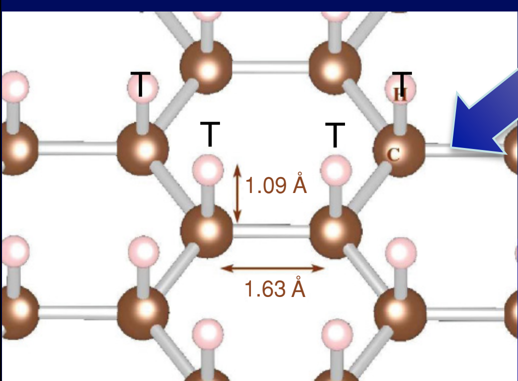
SuperNova
Reactor
Terrestrial
Accelerator
Solar
Atmospheric
Cosmic
Big Bang
PTOLEMY
Cross Section ($\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$ in mb)
Neutrino Energy (eV)



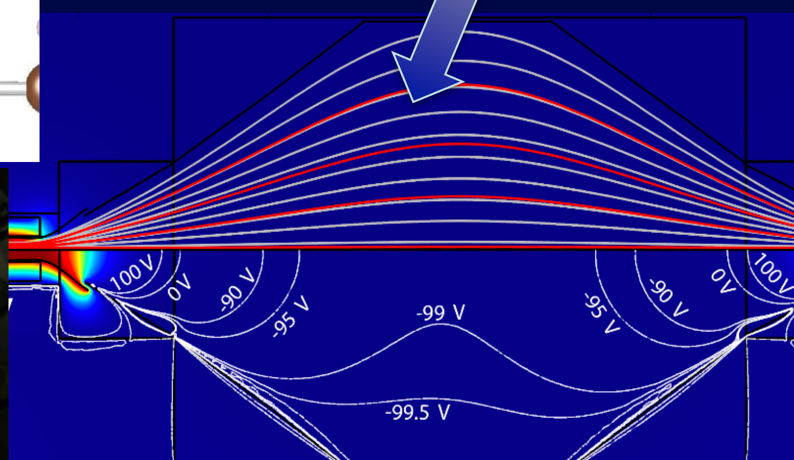
PTOLEMY
Supported by:
The Simons Foundation



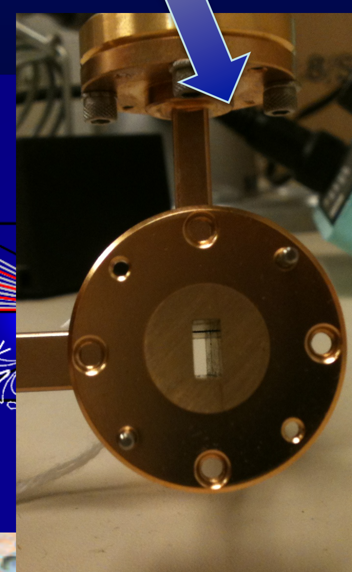
1 mm
TES

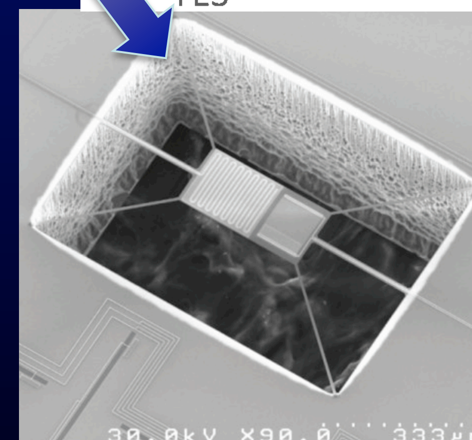


T
T
T
T
C
1.09 Å
1.63 Å



100 V
0 V
-90 V
-95 V
-99 V
-95 V
-90 V
0 V
100 V
-99.5 V





30.0kV X90.0 333μm

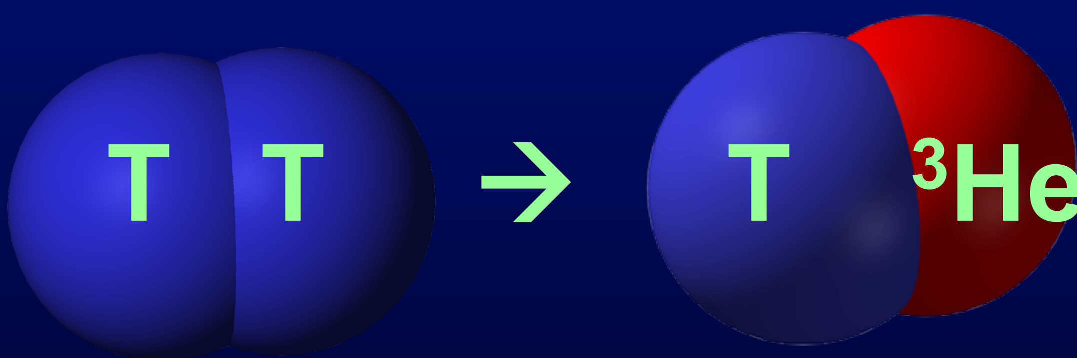
Hydrogen (Isotope) Bonding

Tritium experiments typically use diatomic tritium T^2 where the bond strength is approximately 4eV.

But what happens when one T atom decays?

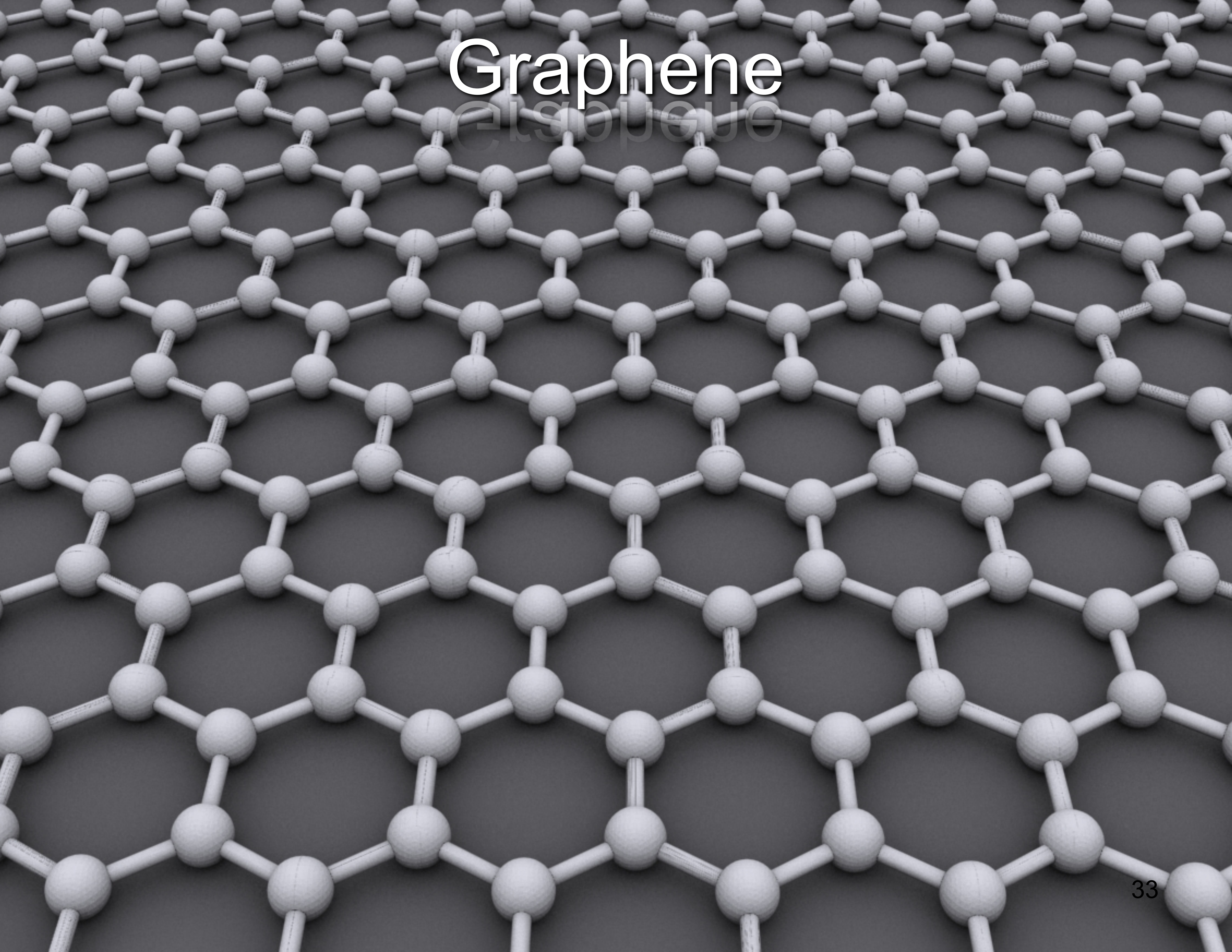
Bodine, Parno, Robertson: arXiv:1502.03497

Answer:



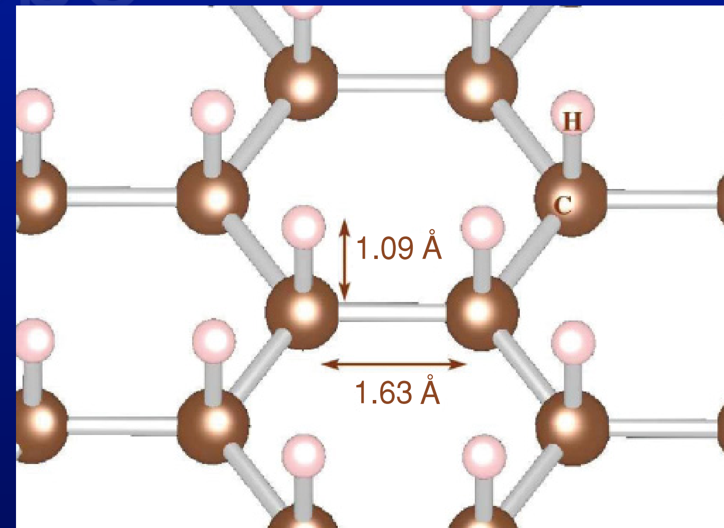
Quantum Mechanics tells us that the outgoing electron energy depends on the change in the binding energy of T^2 to $(T\text{-}^3He)^*$ - smearing >0.4eV

Graphene



Tritium on Graphene

- In the hunt for alternative energies, there has been a great focus on the development of Hydrogen storage systems
  - Hydrogen binds to the surface of graphene in a solid form (6%wt) at room temperature, but with a weak enough binding that the hydrogen can be readily released



Single-sided-hydrogenated Graphene
- Planar (uniform bond length)
- Semiconductor (~Si gap)
- Polarized tritium(?)

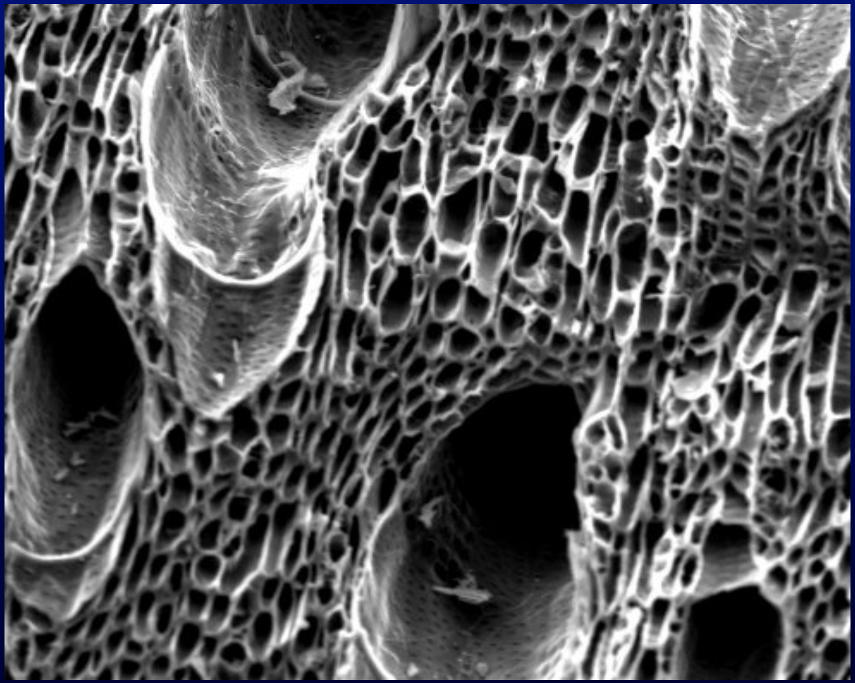
$\sim 3\times10^{13}$ T/mm^2 (~80kHz of decays/mm^2)

Different forms of hydrogenated graphene have a hydrogen binding energy less than 3eV with potentially no binding for He^3

THE Challenge

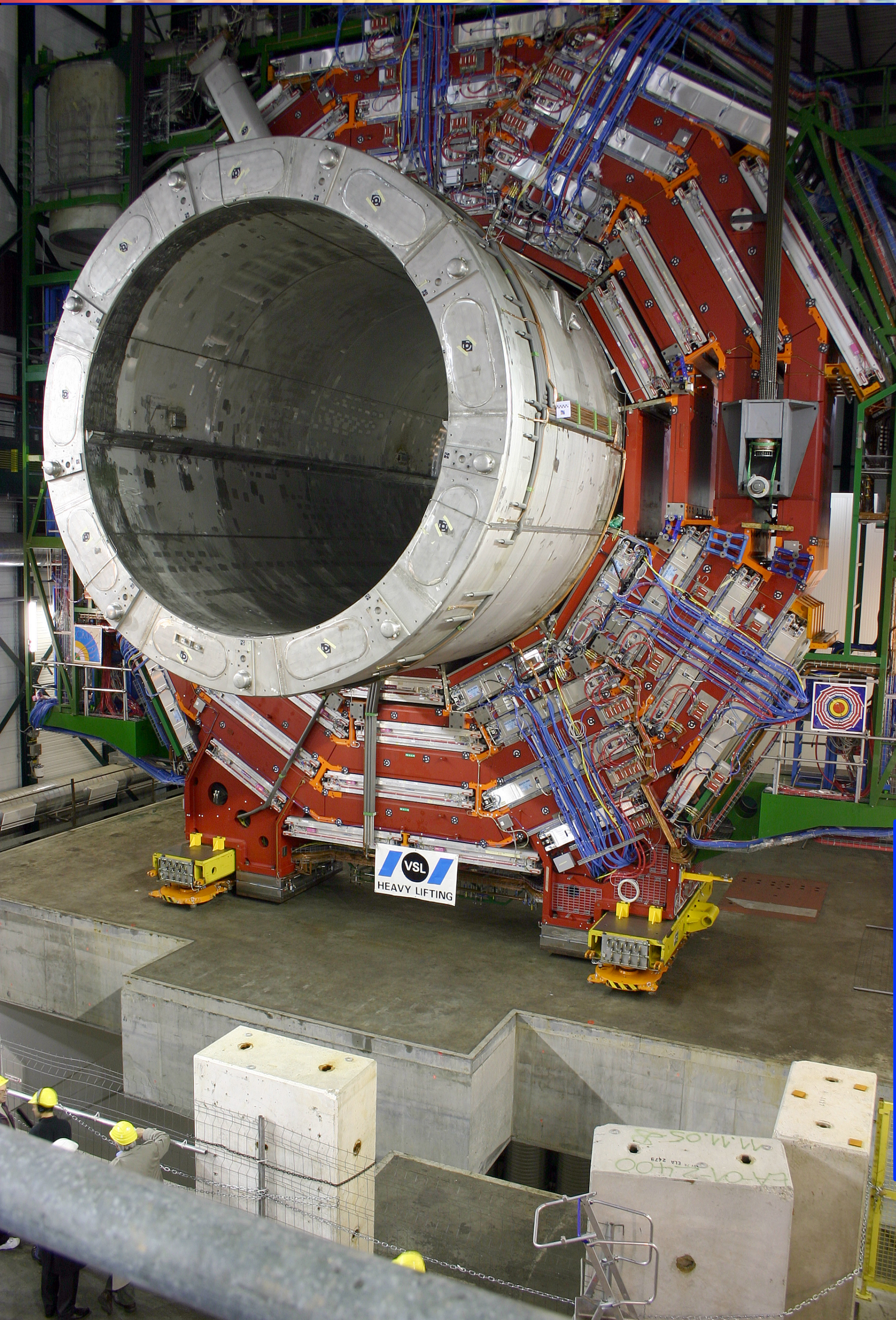
- The largest and nearly insurmountable problem of relic neutrino detection is to provide a large enough surface area to hold at least 100 grams of weakly bound atomic tritium
  - The trajectory of the outgoing electrons from tritium decay must have a clear vacuum path to the calorimeter (up to one or two atomic layers of carbon or up to a few hundred layers of tritium)
  - Need approximately 10^6 m^2 of expose surface area, that's ~200 football fields
  - Cannot be achieved with a flat planar surface – needs nanotechnology and micro-pattern fabrication to solve

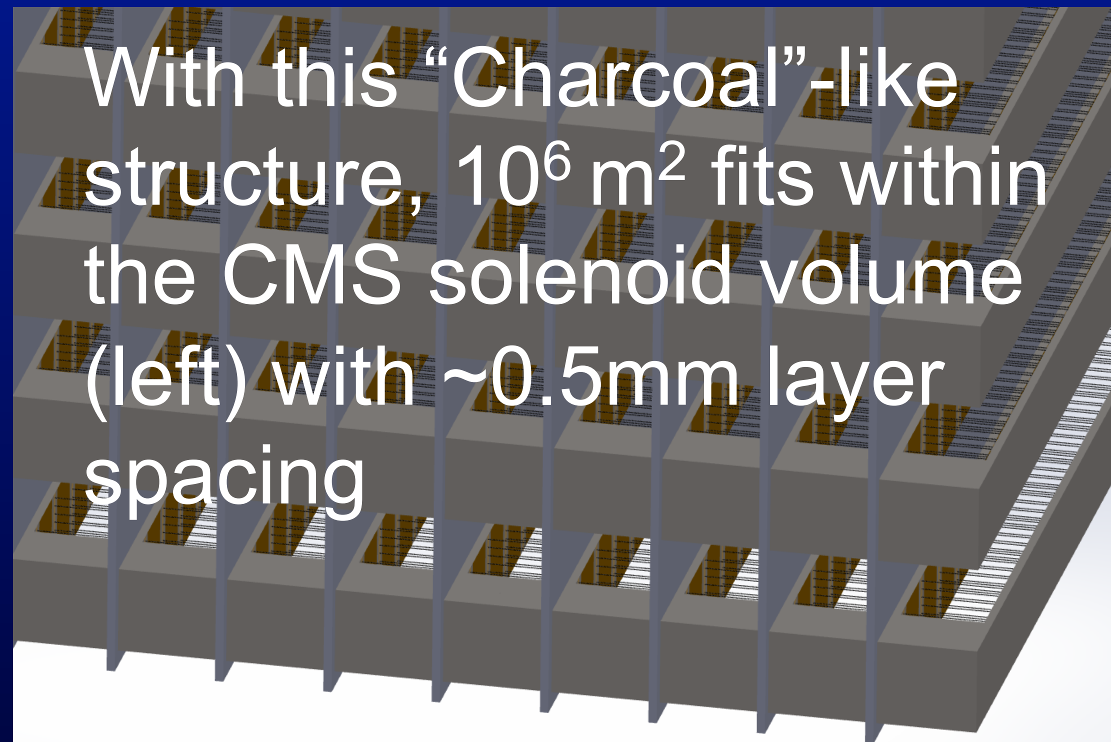
Charcoal



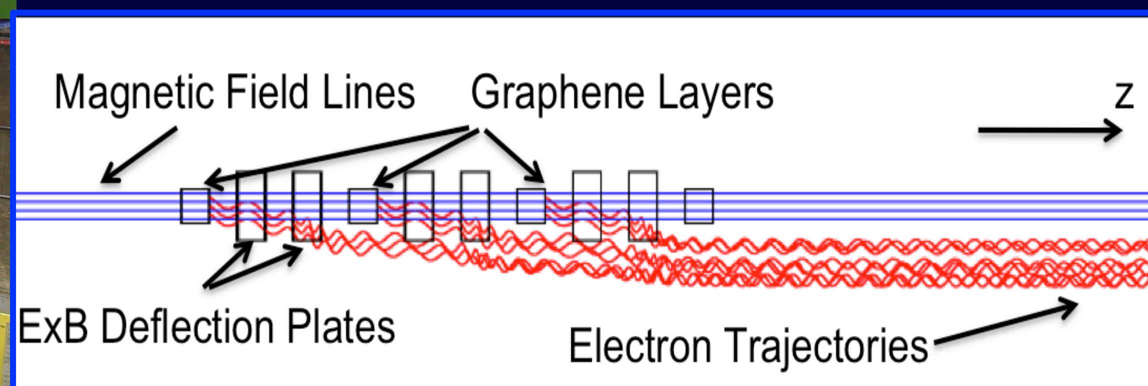
Charcoal
Surface Area ~7×10^5 m^2/kg

CMS Magnet at the LHC





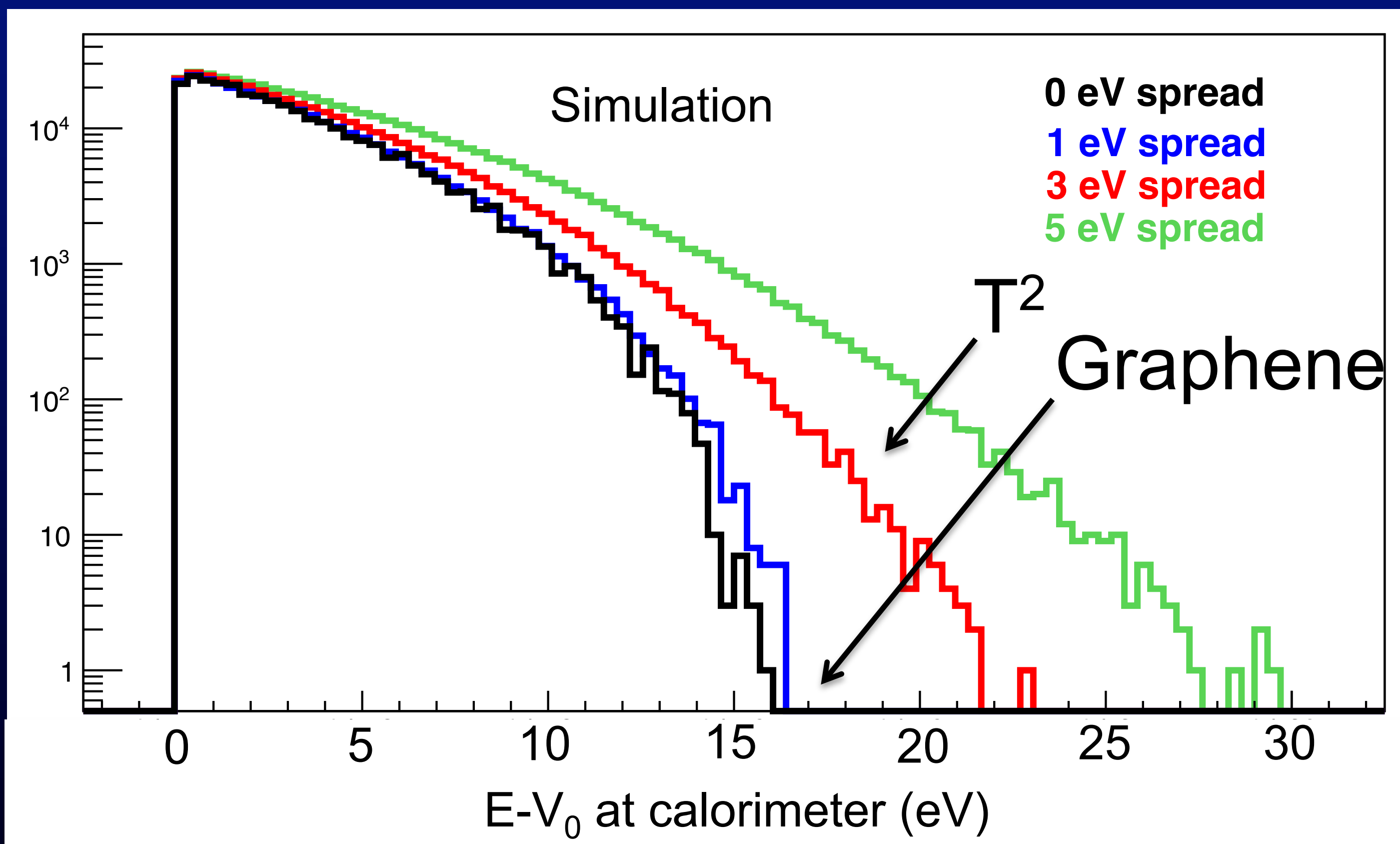
With this “Charcoal”-like structure, 10^6 m^2 fits within the CMS solenoid volume (left) with ~0.5mm layer spacing



Lyman Sptizer, Jr. (1950’s), Van Allen

Sensitivity to Shifts and Smearing

Direct measurement of systematic uncertainties from e^- energy smearing



~10^{14} electrons from GEANT4 simulation (perfect resolution, ~1 month of data with 1µg ^{3}H)

Goals: Measure relative endpoint shifts of graphene compared to T^2 and determined relative energy smearing

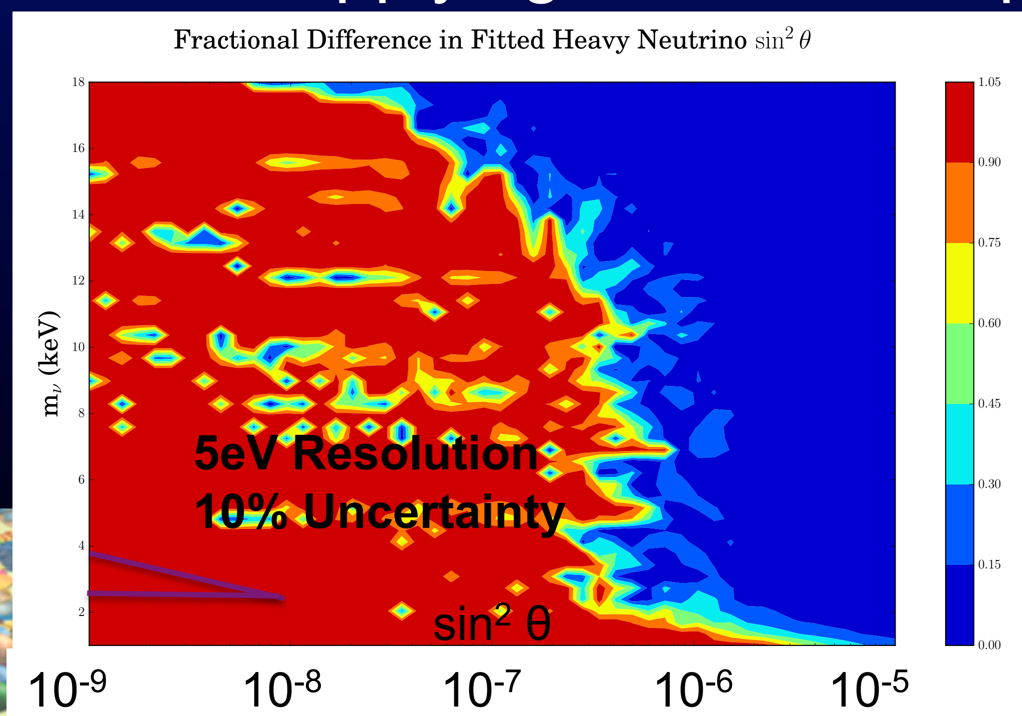
Future: Ultra-weak surface binding below the room temperature stability limit.

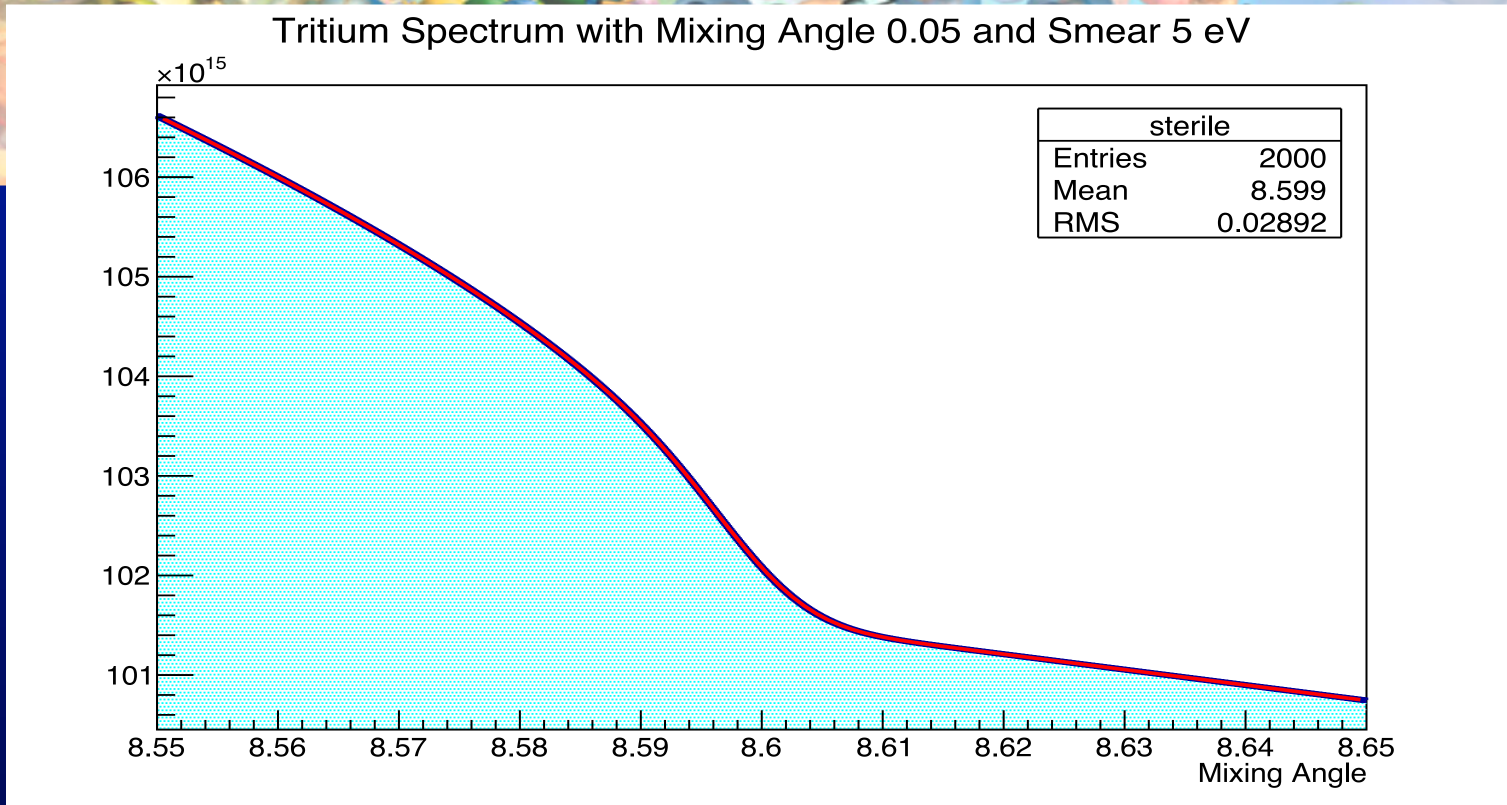
Limiting Systematics

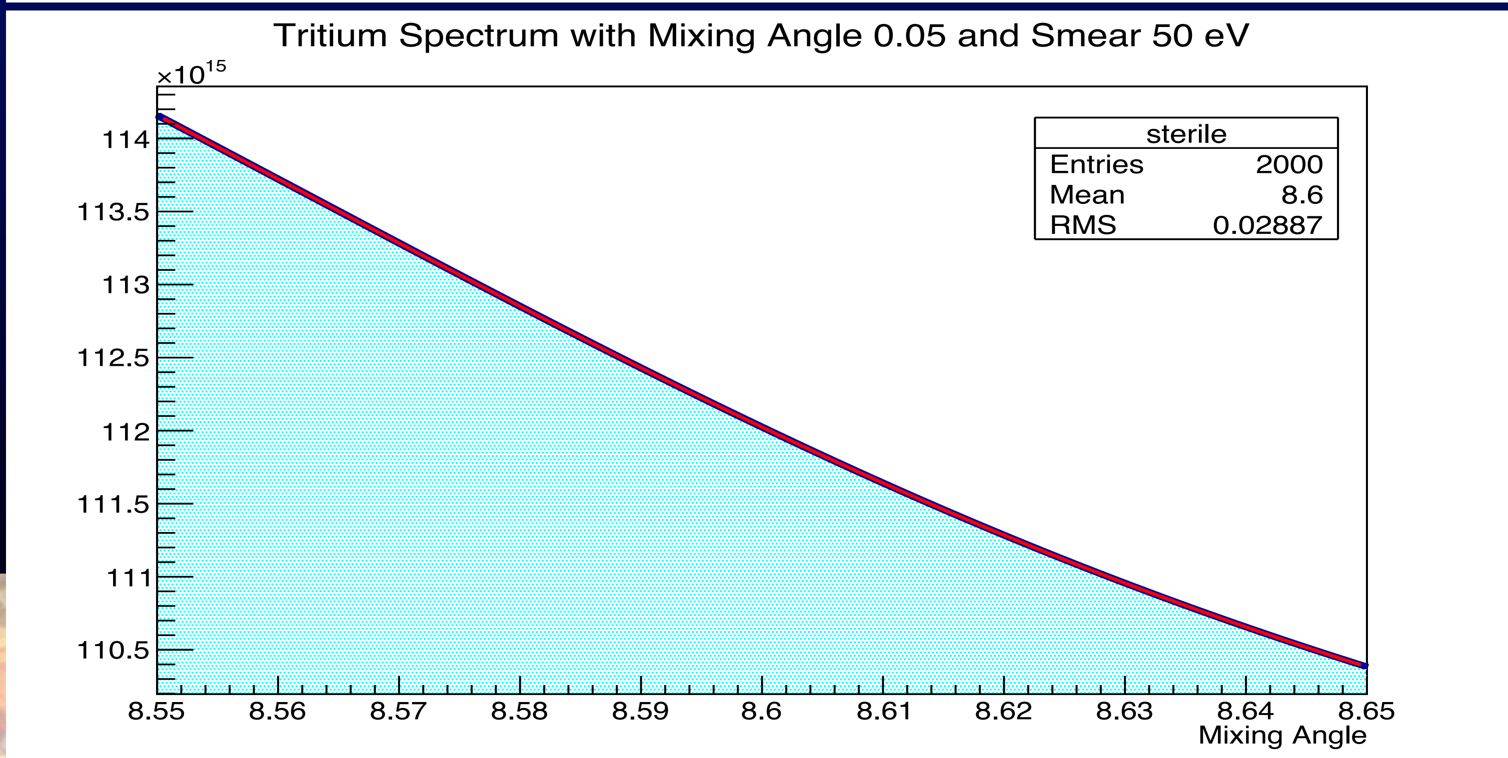
- Expected versus Observed Calorimeter Resolution
  - Single most important systematic:

    Energy Resolution Uncertainty
  - Scanning Base Calorimeter Resolution from 0.1eV to 50eV and fitting with the correct resolution had less effect than using 50eV resolution and applying a 10% shift up and down in the fit

Higher absolute energy resolution visibly important




Tritium Spectrum with Mixing Angle 0.05 and Smear 5 eV
×10^15
sterile
Entries 2000
Mean 8.599
RMS 0.02892
106
105
104
103
102
101
8.55 8.56 8.57 8.58 8.59 8.6 8.61 8.62 8.63 8.64 8.65
Mixing Angle


Tritium Spectrum with Mixing Angle 0.05 and Smear 50 eV
×10^15
sterile
Entries 2000
Mean 8.6
RMS 0.02887
114
113.5
113
112.5
112
111.5
111
110.5
8.55 8.56 8.57 8.58 8.59 8.6 8.61 8.62 8.63 8.64 8.65
Mixing Angle